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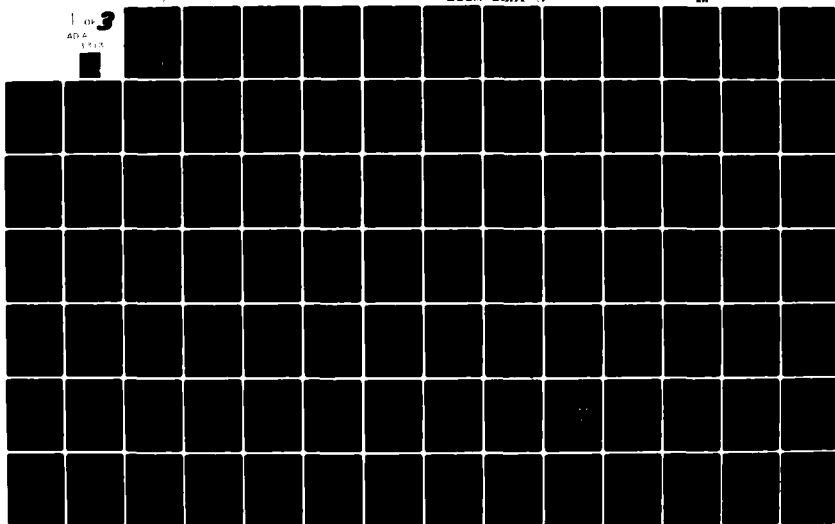
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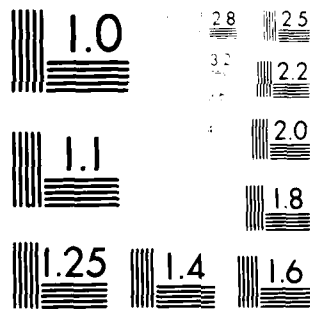
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MM&T PROGRAM TO ESTABLISH PRODUCTION
TECHNIQUES FOR THE AUTOMATIC DETECTION
AND QUALIFICATION OF TRACE ELEMENTS PRESENT
IN THE PRODUCTION OF MICROWAVE
SEMICONDUCTORS

AD A113313

FINAL REPORT
23 August 1977 to 1 March 1981

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Production Division, Procurement and Production Directorate
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Contract DAAB07-77-C-0561

Harris Corporation, PRD Electronics Division
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This project has been accomplished as part of the US Army Manufacturing and Technology Program, which has as its objective the timely establishment of manufacturing processes, techniques or equipment to insure the efficient production of current or future defense programs.

MM&T PROGRAM TO ESTABLISH PRODUCTION
TECHNIQUES FOR THE AUTOMATIC DETECTION
AND QUALIFICATIONS OF TRACE ELEMENTS PRESENT
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SEMICONDUCTORS
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23 August 1977 to 1 March 1981

Object of Study

Establish production technique for the automatic detection and concentration quantification of the trace elements (impurities) in the organic and inorganic compounds and solutions that are used in the fabrication of microwave semiconductors and the determination of acceptable impurity levels.

Contract No.: DAAB07-77-C-0561

Report Prepared by: Dr. James D. Basile and Roy W. Spacie

Appendix A prepared by: Dr. George P. Allendorf

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ABSTRACT

Chemical contaminants in materials used in the production of microwave semiconductor diodes adversely affect the device yield. This report explores the relationship between chemical impurities in the solutions used in PIN diode manufacturing and the final yields. It also describes the applicability of spectral analysis technology to ascertaining critical chemical imbalances in the various reagents and solvents.

A computer-controlled spectrometer was used to measure trace metals at each of 50 subprocesses in the PIN diode production. These measurements were amalgamated to comprise a database which was then subjected to detailed statistical analysis in an attempt to arrive at a specific relationship between chemical contamination and yield. No such relationship was discovered.

The spectral analysis technology proved useful for diagnosing chemical contamination which affected production yield. Specific problems involved in the production process and the resolutions provided through use of spectrometry are discussed.

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GLOSSARY

Aliquot:	contained in exact number of times in another, factional.
Analysis of Covariance:	a statistical technique that combines the features of variance and regression.
Analytic Model:	a set of equations and/or logic statements, generally implemented on a computer, which quantitatively represents the interrelationships that characterize a given system.
Angstrom:	a unit of length (wavelength) equal to one ten-billionth of a meter, i.e., 10^{-10}m .
Boule:	a pear-shaped mass formed synthetically in a special furnace with the atomic structure of a single crystal.
Clustering:	statistical procedures which classify data into recognizable subgroups according to a defined criterion function.
Factor Analysis:	a statistical procedure to find a lower-dimensional representation that accounts for the correlation among variables.
Epitaxial:	having orientation controlled by the crystalline substrate - used of crystals and of the relationship between them and their substrate.
Ionize:	to cause a change in the number of electrons in the outer orbits of an atom such that it exhibits a net electrical charge.
Matrix:	that within which something else originates or develops, e.g., a format for developing computer instructions.

GLOSSARY (Contd)

Mesa:	(~ transistor) structured as a mesa - an isolated hill having steeply sloping sides and a level top.
Nanogram:	one billionth of a gram. (Also used are femtogram [one quadrillionth], picogram [one trillionth] and micro- gram [one millionth].)
PIN:	(~ diode) an acronym formed from "positive-intrinsic-negative" - a semiconductor device consisting of heavily doped p^+ and n^+ end re- gions separated by a lightly doped region which can be regarded as intrinsic.
Plasma:	a gas in which a significant frac- tion of its atoms or molecules are ionized.
Principal Component Analysis:	a statistical procedure for finding a lower-dimensional representation that accounts for the variance among an ensemble of data.
Regression Analysis:	a statistical method concerned with the prediction of one or more variables on the basis of informa- tion provided by other measurements or concomitant variables.
Variance:	the weighted average of the squared deviation of the values in a pop- ulation from the population mean, numerically equal to the square of population's standard deviation.

PURPOSE

The objective of the present Manufacturing Methods and Technology (MM&T) Project is the reduction of microwave semiconductor manufacturing costs through increased product yields. This will be achieved by establishing the correlation between contaminant levels in process materials and their effect upon product yields. These relationships will be used to optimize the manufacturing process toward maximum product yields and minimum unit costs. The project will result in the following developments:

1. An analytical model of the manufacturing process. The model will be implemented in a computer program which will serve as an optimizing control system for the process.
2. A system of batch or lot identification to maintain traceability of contaminants throughout the process, from receiving inspection to the final product.
3. A quantitative chemical analysis system to evaluate contaminants in the materials used in the manufacturing process.
4. A performance specification for an improved manufacturing process control and data management system incorporating these techniques.

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SECTION I

1.1 PROBLEM DESCRIPTION

It is currently estimated that the Federal Government will spend \$47.3 million dollars in 1981 for microwave semiconductor diodes, i.e., for discrete diodes devices which operate above 1 GHz. These expenditures will rise by 20 percent per year for the next four years, buoyed chiefly by increased emphasis in strategic missiles and space systems, communications and electronic countermeasures and ordinances.

In the manufacture of these devices production yields generally are very low, typically in the order of five to seven percent. That is to say, 14 to 20 devices must be fabricated on an average for every usable one produced. The cost of these devices, which range from 10 to 700 dollars a piece, represents primarily labor charges. The intrinsic value of the material is only a few cents.

Any procedure which would improve production yields or limit the labor costs associated with the fabrication of defective devices could represent a significant cost savings for the military.

A major factor contributing to poor production yields is the inclusion of trace amounts of contaminants within the devices' crystalline structures. Contaminating elements in the order of a few parts per billion are often sufficient to degrade, if not destroy, the performance of one of these devices. Lower contaminant levels would reduce production cost through increasing production yields while generally improving electrical performance. Improved device performance would, in many cases, impact the design and overall effectiveness of the electronic systems in which they perform key functions.

Generally, the structure of the microwave device is such as to preclude direct non-destructive measurement of contaminant levels within the device. The causal relationship between contaminant levels and device performance can only be inferred through statistical sampling and destructive analysis of the end product. An alternative to destructive testing, and the approach pursued in the present project, is to monitor the environment experienced by the semiconductor at each stage of its manufacture and from the observed levels of contamination predict the yield assuming a statistically stationary relationship can be estimated between the level of contamination within the environment and product yield.

1.2 THE MANUFACTURE OF MICROWAVE SEMICONDUCTOR DEVICES

Typically, the manufacture of microwave devices is accomplished as a series of batch processing steps. For example, ultrapure silicon is procured as a raw material. A quantity of this material is melted and recrystallized into a boule. The boule is entered into stock. Sometime later a boule is drawn from stock and sliced into many wafers. The wafers are ground and polished and returned to stock. Small lots of the wafers are drawn from stock as required. The process continues in this manner through 50 to 60 production steps. Similarly, the reagents used in the various process steps are prepared and dispensed in relatively small batches or lots. A single store of partially processed devices may serve as a source for several different product lines.

Because the manufacture of microwave semiconductors is a batch process, it is difficult to maintain traceability of the end product. If an end item should fail to perform properly because of some intrinsic impurity, often it is impossible to trace the impurity back to its source or point of ingress. However, to control impurity levels to a few parts per billion, it is

essential that precise traceability be achieved. Therefore, a part of the present program was to devise and implement a system of automatic record keeping and data processing so that yields could be correlated with measurable impurity levels at each step of the process.

Table 1-1 is a list of those chemical elements known to adversely affect the performance of microwave semiconductor devices. These impurities may enter interstitially into the crystalline structure of the device, either on a substitution basis replacing atoms in the normal crystalline matrix, or react chemically with some of the semiconductor materials. In some cases these element impurities may migrate to an interface inducing effects disproportionate to their average concentrations. In most cases the effects of these impurities upon the electrical performance of the semiconductor device can be predicted with a high degree of accuracy if one knows the concentration of each. Unfortunately, the concentrations of these elements within the semiconductor material can be measured at only a few points in the manufacturing process. Where tests can be made on the semiconductor material they are generally destructive and analytical data must be gathered on a sampling basis.

TABLE 1-1. SOME CRITICAL CONTAMINANTS

Aluminum	Copper	Molybdenum
Antimony	Flourine	Nickel
Arsenic	Gallium	Oxygen
Bromine	Germanium	Palladium
Boron	Gold	Phosphorus
Cadmium	Iodine	Potassium
Calcium	Iron	Rubidium
Carbon	Lead	Silver
Cesium	Lithium	Sodium
Chlorine	Magnesium	Tin
Chromium	Manganese	Zinc
Cobalt	Mercury	

The chemical impurities may enter the semiconductor material at any of many points in the manufacturing process. They may be induced from the solvents used for cleaning and etching the crystalline wafers, from the materials used in the formation of epitaxial layers or from the reagents used in any of the 50 to 60 steps of the manufacturing process.

It must be assumed that all of these contaminants are present to a greater or lesser extent in all of the reagents used in the manufacturing process. However, the semiconductor material is not equally susceptible to contamination at each step of the process. For example, the silicon is susceptible to contamination by oxygen only at elevated temperatures. Therefore, it is not sufficient to know the concentration of these contaminants in each reagent, but one must also know the transfer ratio associated with each element at each step of the process. That is to say, one must know the quantitative relationship between the level of a contaminant in the reagent and the amount of contamination it can be expected to induce into the semiconductor material. Little is known about these transfer ratios. A major task of the project was to explicitly define the manufacturing process in terms of the interrelationships between the reagents and the semiconductor material and to quantify the transfer ratios of pollutants. Once the ratios are established, it remains to set threshold levels consistent with acceptable yields.

Theoretically, one might analyze the chemical composition of the semiconductor material at each step of the manufacturing process, aborting a batch if it is found to be excessively contaminated. Unfortunately such an approach is neither practical nor economical. The semiconductor material is available for testing at only a relatively few points in the manufacturing process, and where it is available it is in a solid form which does not readily lend itself to chemical analysis. Further, chemical analyses of elements to a few parts per billion

are generally extremely expensive and require highly skilled technicians operating with meticulous care. Thus, the costs associated with such an approach would soon outrun any economic gains which may accrue from improved yield. For these reasons a fundamental part of the proposed program was to develop a testing program which was capable of providing the necessary control data within the economic constraints of improved yields.

A detailed description of the microwave semiconductor device technology for PIN diodes and tuning varactors is given in Appendix A. This appendix addresses those stages in the production cycle that are influenced by contaminants and describes, in detail, the device products' correlation to the manufacturing process.

1.3 SPECIFIC PROBLEM

As discussed in the previous sections, and in Appendix A, there are uncertainties in processing semiconductor devices in reasonable yields consistently. Controls for times and temperatures are known to be quite good. The most significant unknown is the variability of the chemical reagents and deionized water used in wafer fabrication. In addition, although ambient conditions are usually considered to be quite well controlled with laminar flow, ultrafiltration and frequent particle counts, the chemical nature of airborne contamination is probably the next most significant unknown. The well-known cyclical history of the manufacture of certain microwave semiconductor devices bears these facts out. Frequently, certain devices go out of production; the company is said to have "lost the recipe" temporarily. Then, as mysteriously as the problem arose, its nature being such, the problem disappears; yields return to original levels and production once again returns. The cost to the Government in these situations is significant. Did the problem disappear because a particular lot of reagent material was used up or replaced?

The problem could have been caused by variability within the manufacturer's specification of some critical contaminant in a reagent, as no quantitative tool is available to monitor on-line each batch for impurity levels and types.

The present project attempted to form the basis for an automatic test and control system, which would include all the appropriate sensors to detect impurity levels in the chemical reagents and particulate matter which might be present in a microwave semiconductor process. This control system would have the capability of analyzing all the chemical inputs to the process, solid, liquid and gaseous. The functions of this detection and control system was to have been several: to provide warning of excessive contamination as early in the process as possible; to allow contaminated material to be discarded, rather than accrue further manufacturing costs; to be able to identify specifically the critical contaminants to microwave technology, and the threshold levels necessary to precisely control the process; to provide lot traceability throughout the process so that final yields of end products could be correlated with known contamination levels and appropriate yield improvements could be made.

The benefit to the Government and to the microwave industry arising from such a project would be significant. The keystone of an overall process control and monitoring system would be the analytical tool necessary to provide the answers as to what contaminants affect device yields, what would be their allowable levels and what steps should be taken to minimize their effects upon semiconductor yields.

The project, if successful, could readily be extended at some future date to include other sensors. Temperatures, flow rates, real-time gas stream analyses, pressures, residual atmosphere under high vacuum are all areas which could be readily controlled and monitored by a computerized system. Historical information on the performance of a piece of equipment, comparison with present performance, and trend information would be readily available.

SECTION II

TECHNICAL APPROACH

2.1 GENERAL PLAN OF ATTACK

The solution to the problem was to be based on, and developed out of, an actual operating microwave semiconductor manufacturing facility. The data on which the solution was to be based could be meaningful only if they were derived from an on-line operating process and interpreted by individuals actively engaged in the current technology and manufacturing practices. At each stage of its evolution the solution was to be tested against the realities of a microwave production line. Recognizing the requirements, PRD teamed with Microwave Associates, Incorporated, of Burlington, Massachusetts, which was a major supplier of microwave semiconductor devices to the Army for many years and was currently manufacturing a high voltage PIN diode on which the study could be based.

PRD and Microwave Associates were designated prime contractor and subcontractor, respectively. PRD was charged with full responsibility for execution of the project and all liaison with the Procuring Agency, Microwave Associates, under the direction of PRD, was to perform the major portion of the project work.

The instrumentation procured under the project was installed in the facilities of Microwave Associates in Burlington, Massachusetts, and operated by them. All chemical analyses were made by Microwave Associates.

PRD developed the analytical model and performed all statistical analyses. The computer requirements were implemented on a UNIVAC 1108 computer resident at PRD, Syosset, New York. Data was entered directly into the computer system via a remote terminal at Microwave Associates. For the most part, PRD used Biomedical Computer Programs developed by the Health Sciences Computing Facility, Department of Biomathematics, School of Medicine, University of California, Los Angeles, California. These programs provided a wide variety of analytic capabilities that ranged from plots and simple data descriptions to advanced statistical techniques. Special applications programs, where required, were written in FORTRAN IV.

Microwave Associates provided the semiconductor production facilities and technology, fabricated the high voltage PIN diodes, performed all chemical analyses and evaluated the yields. PRD provided project management, system engineering, computer facilities, software applications and performed all statistical analyses.

The team's approach to the problem was first to develop an analytical model of the semiconductor manufacturing process. The model would relate the concentration levels of each contaminating element in each reagent to the product yield. These quantitative relationships would be expressed in terms of a set of parametric transfer ratios or coupling coefficients. The model would be exercised in parallel with the operation of the production line. Each intermediate step, as well as the final yields of the process, would be correlated with the corresponding step predicted by the model.

A system of item identification would be developed by which traceability could be maintained for each of the intermediate steps throughout the manufacturing process.

If and when reasonably stable correlation coefficients could be established between the model and the process, the model would be reduced to a set of linear-programming objective functions suitable for optimization against any given set of constraints. From these a set of contaminant threshold levels and monitoring points would be established which would assure a specified product yield/cost target.

Finally, PRD and Microwave Associates together would generate a specification for a system which could monitor and optimize a microwave semiconductor manufacturing process.

To acquire the necessary chemical analysis data a computer-controlled inductively coupled argon plasma emission spectrometer was to be procured and installed at Microwave Associates' facility in Burlington, Massachusetts.

2.2 PROGRAM PLAN

As originally conceived the program was to have been accomplished in a period of 15 months, starting with the award-of-contract on July 29, 1977 and terminating on October 27, 1978. A detailed plan of the effort was jointly prepared by PRD and Microwave Associates and presented in the First Quarterly Report (23 August to 23 November) in the form of a PERT chart.

Because of the long lead-time involved, the first task which was to be undertaken was the selection, procurement and installation of an instrument or instruments capable of rapidly analyzing a substance for each of 35 trace elements in concentrations of 10 to 100 parts per billion (ppb) and the training of a staff of operators.

Concurrently, a microwave product line was to be selected and a detailed definition of the manufacturing process developed.

Following that, work was to start on the design and implementation of the analytic model and on the detailed design of the experiment. The latter would include the test and control runs to be made, the materials and instruments needed to make the runs and a plan for the acquisition of test data. With the completion of the test data acquisition plans, work was to begin on the planning and implementation of the computer programs for managing and reducing this data. It was planned to complete all of the above by mid-January 1978 at which time the analytic instrument would have been installed and its operating personnel would have gained some experience in its use.

The period from mid-January through mid-March 1978 was scheduled for gathering experimental data on which to complete the analytic model, that is, determining its transfer ratios. Throughout that period, special experimental runs were to be made using deliberately contaminated (doped) materials. By the end of March, sufficient data would have been assembled to allow a preliminary verification of the model to be conducted. This was to be accomplished using the model to predict the yield as one or more batches of wafers were processed. The remaining time through August 1978 was to be devoted to refining the model and its optimization programs by gathering operating data from an otherwise normal production line process.

Approximately 4500 wafers were to have been processed. The exact number of wafers was to have depended upon Microwave Associates' production schedule for the selected diode during that period.

Once the form of the analytic model was verified, work was to begin on the development of a system specification defining the integration of the new technique into a viable manufacturing process.

2.3 PROGRAM EXECUTION TO DATE

In terms of the major tasks outlined in the original PERT plan, the following were accomplished:

- o A spectrometer and certain ancillary instruments were procured and set in operation, and several operator/analysts were trained.
- o A limited number of baseline analyses were run.
- o A high voltage PIN diode manufacturing process was defined.
- o An analytic model of the selected manufacturing process was developed in minimum form without scaling or verification.
- o Statistical analysis programs were readied for processing data on a UNIVAC 1108 computer.
- o Limited statistical analyses were performed on the available test data.
- o Ancillary computer programs were prepared and debugged for storing and processing the chemical analyses and test data.

The lack of an adequate test data precluded the completion of a model for predicting manufacturing yields or to establish the feasibility of the project's objectives. Of the 4,500 sample runs anticipated in the original program plan only 90 were accomplished, of which many were invalid or of doubtful value.

SECTION III

PROGRESS

3.1 INSTRUMENTATION

The primary instrumentation selection was discussed at some length in Appendix B of the First Quarterly Report.

Because it was assumed that all 35 contaminating elements would be present in every sample it was thought that it was necessary to measure all of them until such time as one or more were proven to be of little or no consequence. Among the chemical analyses techniques considered were: mass spectrometry, neutron activation, atomic absorption spectrometry, atomic emission spectrometry, x-ray fluorescence, anodic stripping, ion-selective electrodes and various surface analysis techniques including ESCA, ISS, Auger and SIMS. The study showed that a computer controlled plasma coupled emission spectrometer offered the maximum analytical capability and lowest cost per sample of any. At the time the only instrument of that type was manufactured and marketed by Jarrell-Ash Division/Fisher Scientific Company, Waltham, Massachusetts (Jarrell-Ash Plasma Atomcomp, Cat. No. 96-975).

The Atomcomp could measure simultaneously 27 of the 35 contaminant elements of interest and could measure each to the level of 10-100 parts per billion. Among the elements it could not measure were 4 halogens (fluorine, chlorine, bromine and iodine) whose spectral lines occur at frequencies beyond the spectral range of the device's optical components. Carbon, cesium and rubidium produce spectral lines so close in frequency to lines of one or more of the 27 elements they could not be resolved with the spectrometer's dispersive system. The basic

system was capable of measuring oxygen but in order to do so the entire spectrometer would have had to have been evacuated. Jarrell-Ash manufactured a spectrometer model which could be evacuated but it was nearly twice the price of the system which was purchased.

Six major problems were encountered in the use of the emission spectrometer. First, while chemical standards in aqueous solutions were readily available from several chemical supply houses, standards in organic solutions were not. After much searching, standards were obtained from a division of Continental Oil Company. These standards were formulated as typically 500 to 900 ppm of the metallic elements in a hydrocarbon oil. These standards were used as aliquots and diluted in the appropriate organic base, without the need for solubilizers.

Second, when running organics, molecular carbon was deposited on the inner surfaces of the plasma torch. The carbon absorbed the infrared radiation causing the glass of the torch to overheat. The torch was designed to provide a protective shield of argon gas around the plasma. This served to cool the glass and to flush the molecular carbon away. It was found that by careful adjustment of the gas flow, the rate of carbon accumulation could be greatly reduced but not totally eliminated. As a result, when organic materials were analyzed, the torch required frequent cleaning and adjusting.

A third problem was concerned with attaining a constant aspiration rate for the sample. The organic solvents of interest generally are highly volatile. When these materials were introduced into the aspirator, the aspiration rate was found to be unstable and quenched the plasma torch. In the Jarrell-Ash spectrometer, the sample was normally drawn through a capillary tube by a negative pressure created by the Venturi effect of the aspirator. The aspiration rate was controlled by regulating the pressure of the argon gas fed to the Venturi jet. For samples

which had high vapor pressures the rapid reduction of pressure in the immediate vicinity of the Venturi tended to vaporize rather than atomize the material, thus resulting in erratic pressure variations. The operator was constantly striking a balance between the loss of aspiration and blowing out the flame with a burst of material. One solution was to introduce the sample material under positive rather than negative pressure. This was accomplished by using a positive displacement pump to inject the material at a precisely controlled rate. To minimize any pulsation in the flow which might be induced by the pumping action, a peristaltic type pump was selected.

A fourth problem in analyzing organics was concerned with the intense green color observed at the base of the plasma torch. Upon investigation it was found to be the product of molecular carbon species. To minimize possible interference from those bands, it was found that the plasma torch had to be precisely positioned to assure that the region of maximum atomic emission was scanned. The intense green color suggested that its principal energy bands were between 5250Å and 5750Å and fortunately the spectrometer, as configured for this application, did not monitor any line between 4632Å (Ni) and 5890Å (Na). Furthermore, second order dispersion of the green would fall (above 10,500Å) in the far infrared, beyond the range of the spectrometer's optical system and beyond 7664Å (K), the highest line which was monitored. However, carbon, which is a major constituent of all organics, exhibits a strong line at 1930Å just 4Å from the 1936Å line of arsenic, a trace element of interest. For any element whose emission is 2500Å or less, corrections had to be made for emissions from such molecular products as C=N, C=C and O=H. This would include nearly half of the 27 trace elements of interest. To help resolve these interferences, the elements which are to be analyzed and the appropriate wavelengths under

investigation were identified to scientists at the Analytical Chemistry Laboratory at Watertown Arsenal. They identify the possible interferences. Where interferences existed, quantitative techniques were developed to automatically correct the data in the computer to improve the accuracy of the analysis.

A fifth problem concerned the need for background compensation. The project was to determine quantitatively what levels of impurities in process chemicals affect device performance. From what was known at the time, it appeared that meaningful data had to be obtained on concentrations in the parts-per-billion range. These levels approached the limit of detection for the spectrometer. At such concentration levels the background emission intensity at a given exit slit may be more than 50 to 75 percent of the total intensity falling upon the photomultiplier tube. In making accurate measurements in the parts-per-billion range, it was necessary to compensate for the background emission falling on each exit slit, as well as for any slow instrumentation drift. This was accomplished by frequently standardizing the instrument against standard solutions having compositions closely approximating those of the sample under test. This technique was very exacting and time-consuming. It worked well in compensating for slow instrumentation drifts and for changes in background levels which were proportional to the line intensity or to the intensity of the internal standard. It presupposed however that the chemical and physical characteristics of the sample were comparable to those of the standard. If, for any of a variety of reasons, e.g., a sample of different viscosity, the background intensity varied independently of the signal, a significant error could be introduced. A more effective method was to measure the background at each exit slit each time the line intensity (i.e., line plus background) was measured.

Jarrell-Ash was then manufacturing a device which automatically corrected for background illumination at each exit slit each time a measurement was made. It dynamically rotated the

spectral array through a very small angle so that the photo-multiplier tube sensed first the intensity of the spectral line plus the background intensity immediately adjacent to the line. The device consisted of a small (approximately 3 mm thick) glass plate inserted in the polychromic light beam immediately behind the entrance slit. The plate was rotated about a vertical axis, normal to the optical plane. The plate, driven by an electrical stepping motor, alternately assumed one of two angular positions, shifting the spectrum a few angstroms from right to left and back again. This permitted alternately making a set of measurements at the peak of each line response followed immediately by a similar set offset from the peak by a fixed amount. The computer compared the value of intensity at the peak of each line to the measured value of background interference immediately adjacent to each line rather than to some assumed (standardized) level. The device dramatically improves the accuracy of the spectrometer at low concentration levels.

A spectrum shifter of this type was purchased from Jarrell-Ash and was delivered and installed in April 1978.

A sixth major problem concerned communicating the data from the spectrometer to a remote computer, namely the Univac 1108 at Syosset, New York. The Atomcomp spectrometer employed a PDP-8 computer and a dual disc drive, only one disc of which was used. One would have liked to arrange it so that the PDP-8 could interface with the Univac 1108 directly or via the unused disc. Jarrell-Ash refused to supply any software programming documentation, holding that the programs were proprietary. They recognized that arranging such an interface had merit and were planning to address the problem at some future date but could not commit the necessary manpower to the task at that time. The problem was solved by using an acoustic coupler to transmit the data supplied the TTY printer via telephone line to the Univac 1108. This arrangement was error prone and much time and effort was expended in checking and retransmitting analysis data.

During the installation of the spectrometer at Microwave Associates, service engineers from Jarrell-Ash provided training in many aspects of the instrument, including sample preparation, matrix construction, operation, troubleshooting, and preventive maintenance. As an extension of that training, three people attended a one week intensive course of study at the facilities of Jarrell-Ash Division, Waltham, Massachusetts. The formal training course emphasized spectrochemical theory and refinements in analytical technique. As a consequence of the formal training, and of the experience accrued from almost constant operation of the instrument from the time of its installation, the analytic skills required for the project were gradually developed. The training of operators of the spectrometer proved to be far more time consuming than had been originally planned. Although the operation of the spectrometer could be mastered readily by a technician within a few days it required months of practice and hundreds of samples before reliable results could be consistently produced. Microwave Associates assigned their most highly skilled laboratory technicians to its operation under the direct and nearly constant supervision and surveillance of one of their most experienced senior research chemists.

The spectrometer, although it incorporated a computer for acquiring and processing much of the test data, was far from being automatic. It required at least one hour of maintenance for every three to four hours of operation. Most of its controls were manual rather than automatic and their adjustments were highly subjective, e.g., the position of the torch, the aspiration rate, etc. The spectrometer would accommodate the testing of many samples in rapid succession provided the samples were nearly identical in chemical and physical characteristics. If samples of widely different species were to be analyzed it might take several hours to readjust and recalibrate the instrument.

The Model 90-750 Atomcomp spectrometer proved to be a highly precise instrument when operated by highly skilled scientists but could not be considered sufficiently developed to serve as a production instrument. Relatively simple modifications and more adroit use of its computer, however, would improve markedly its usefulness in that area.

During the initial planning of the project it was assumed that facilities would be available at Microwave Associates for automatically measuring the electrical characteristics of each diode device as it was produced. The device was to employ a micropositioner under computer control to place a stylus in electrical contact with each diode on a wafer in turn. The computer would control test equipment in making three electrical measurements on each diode and would automatically compute the exact yield of each wafer. This equipment, however, was not available to the project and yield had to be determined by manual measurements.

3.2 PROCESS SELECTION AND DEFINITION

The manufacturing process which was selected was that for a 1000 volt mesa PIN diode (type JANTX-IN5710). The device was selected for the following reasons:

- o It was a mechanically simple device which exhibited relatively few failures resulting from misalignments or improper assembly.
- o Microwave Associates had manufactured the device in large numbers and had amassed extensive experience in its manufacture.
- o Its manufacture had exhibited poor and erratic yields.
- o The Army was currently using the device in large numbers.

- o Microwave Associates had developed well defined operator procedures for its fabrication and test.
- o Microwave Associates anticipated they would have a production line for the device in operation throughout the life of the project.

Figure 3-1, Mesa PIN Diode Manufacturing Process, is a flow diagram of the selected process.

3.3 DATA STRUCTURES

Data acquired by Microwave Associates has tagged with an identifier indicating the run number, number of wafers in the run, and the wafer identification number. All references to particular wafers will utilize this format:

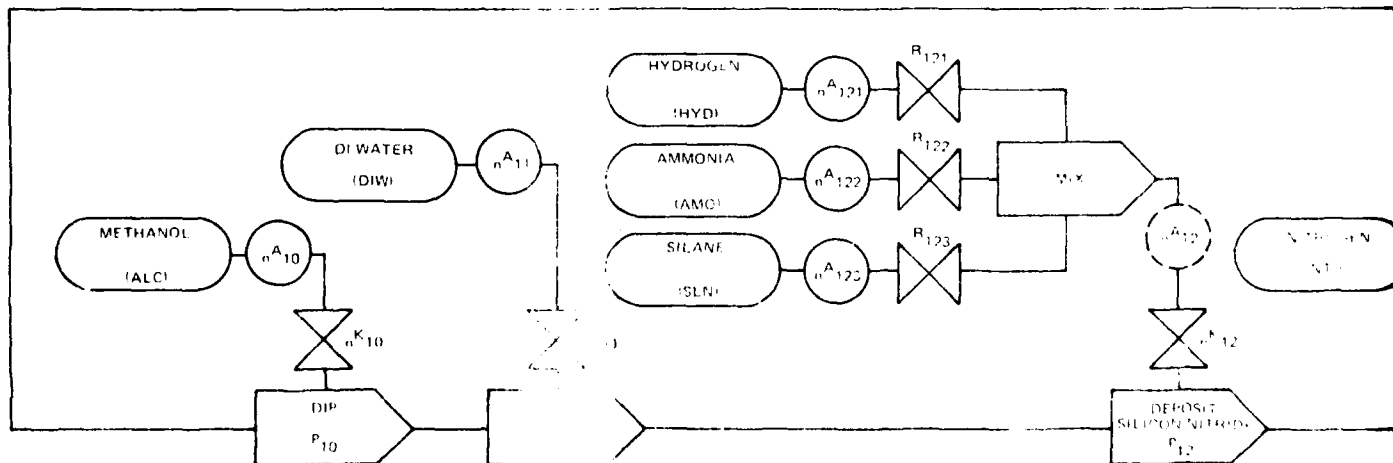
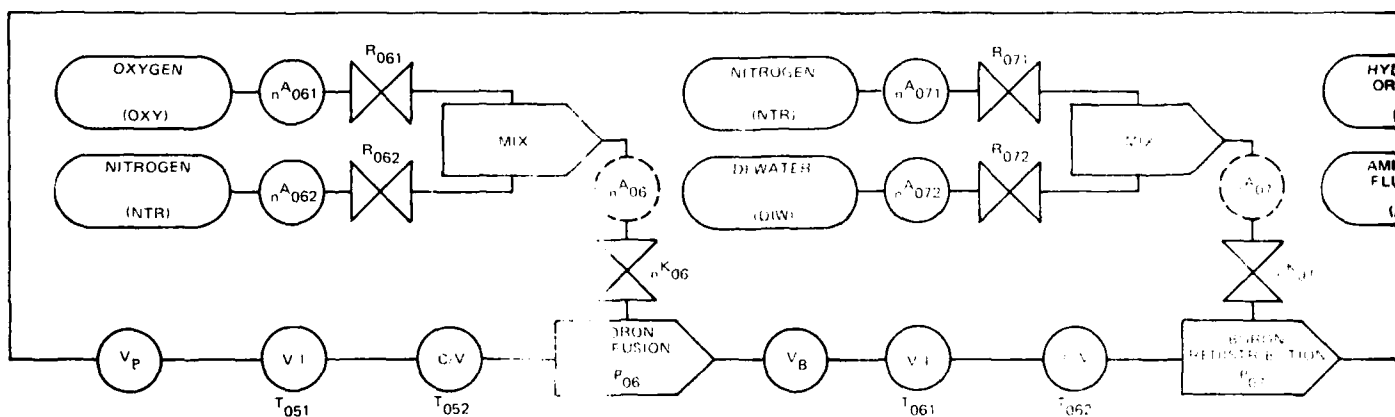
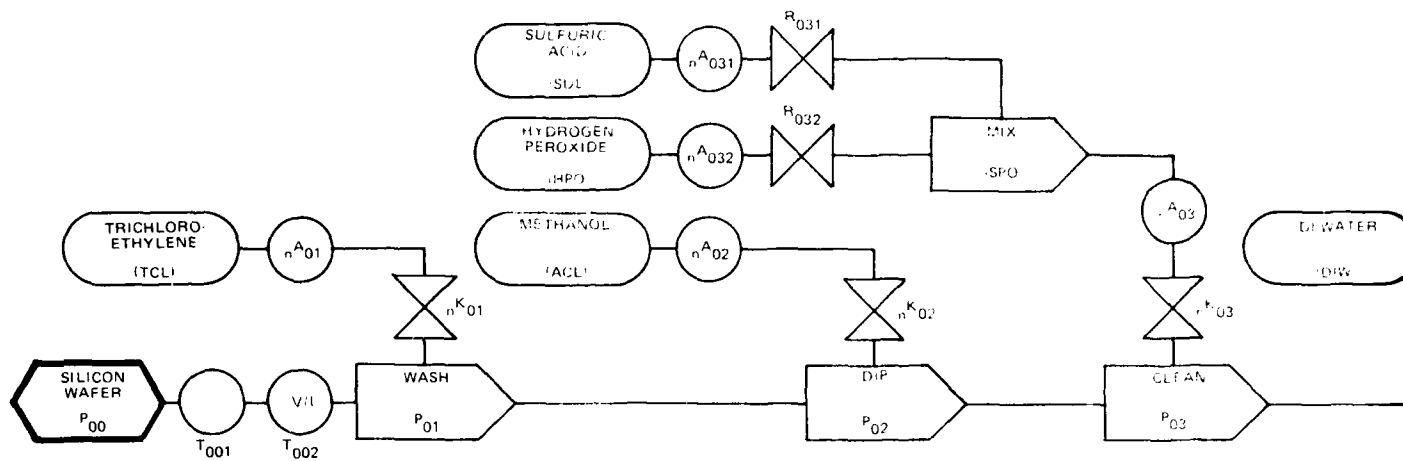
GXXXYY.ZZ .

where

G refers to a run pertinent to this project;
 XXX is to the run number (001 to 999);
 YY indicates the number of wafers in the run;
 ZZ is the wafer identifier within the run.

Microwave Associates collected and transmitted to PRD data for nineteen runs (95 wafers). The data for each wafer within a run consisted of measurements of impurities within production solutions of twenty-seven chemicals at each of fifty substations, as well as twenty-five electrical measurements for a total of 1375 measurements for each wafer. These measurements were transmitted in triplicate over communications lines to PRD. Once received the three records were compared and verified and consistent transmissions were placed in the database.

Figure 3-2 is a Schmoor describing the present state of the database. For each wafer an 'X' indicates stations at which data has been acquired, transmitted, and stored. Runs 0-19 are essentially complete and represent the database used for subsequent investigation and analysis.



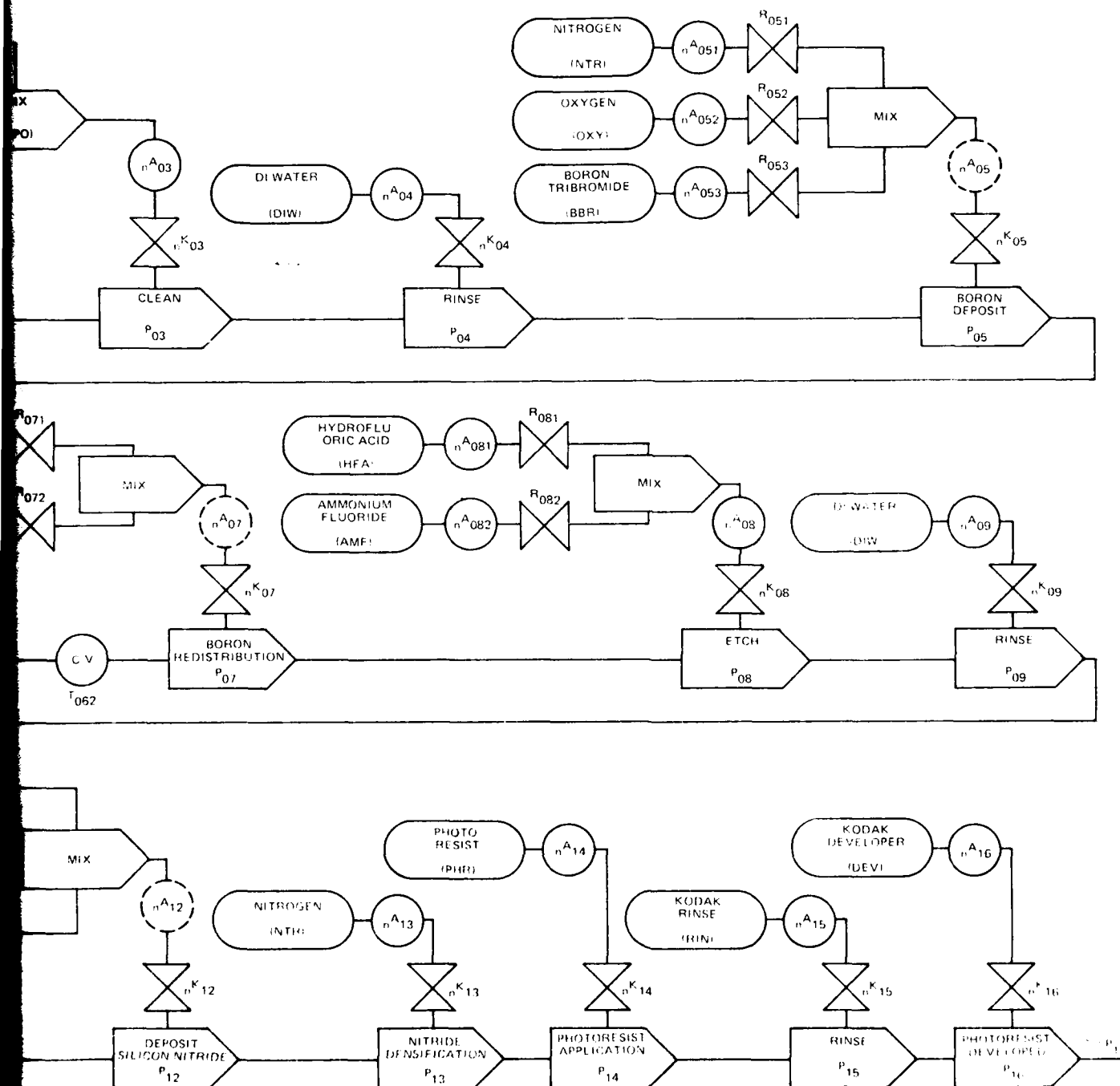
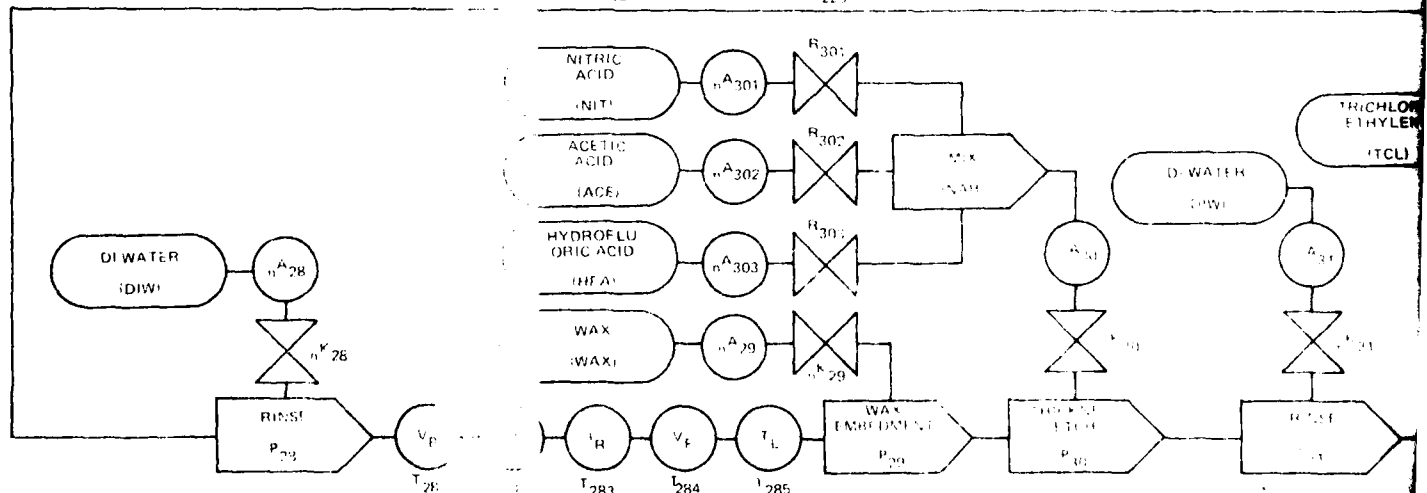
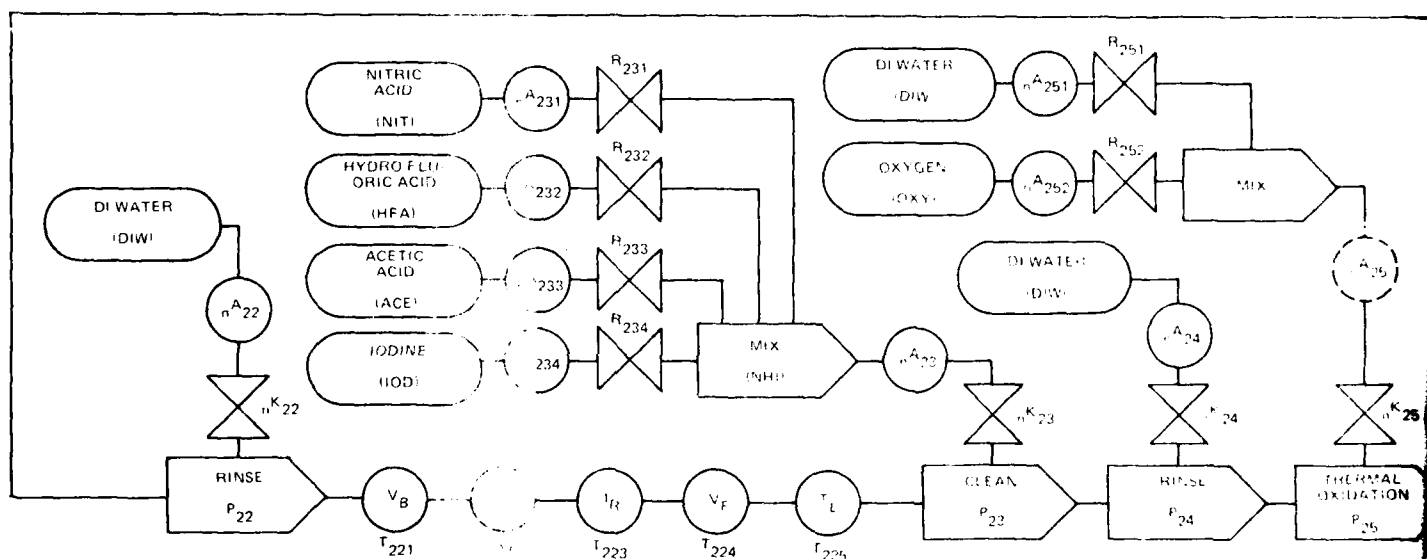
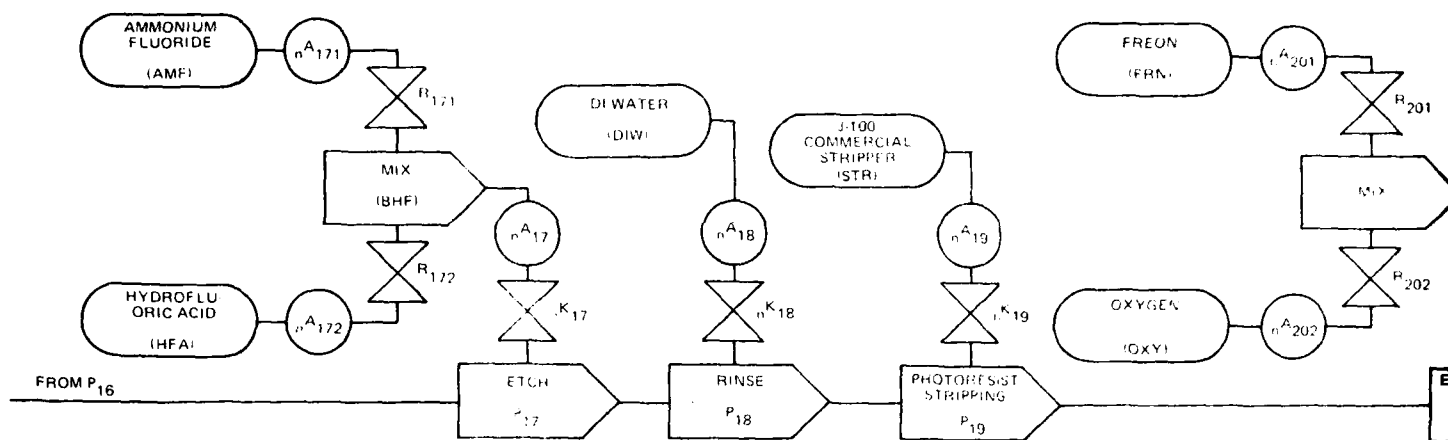


Figure 3-1. PIN Diode Manufacturing Process (Sheet 1 of 3)



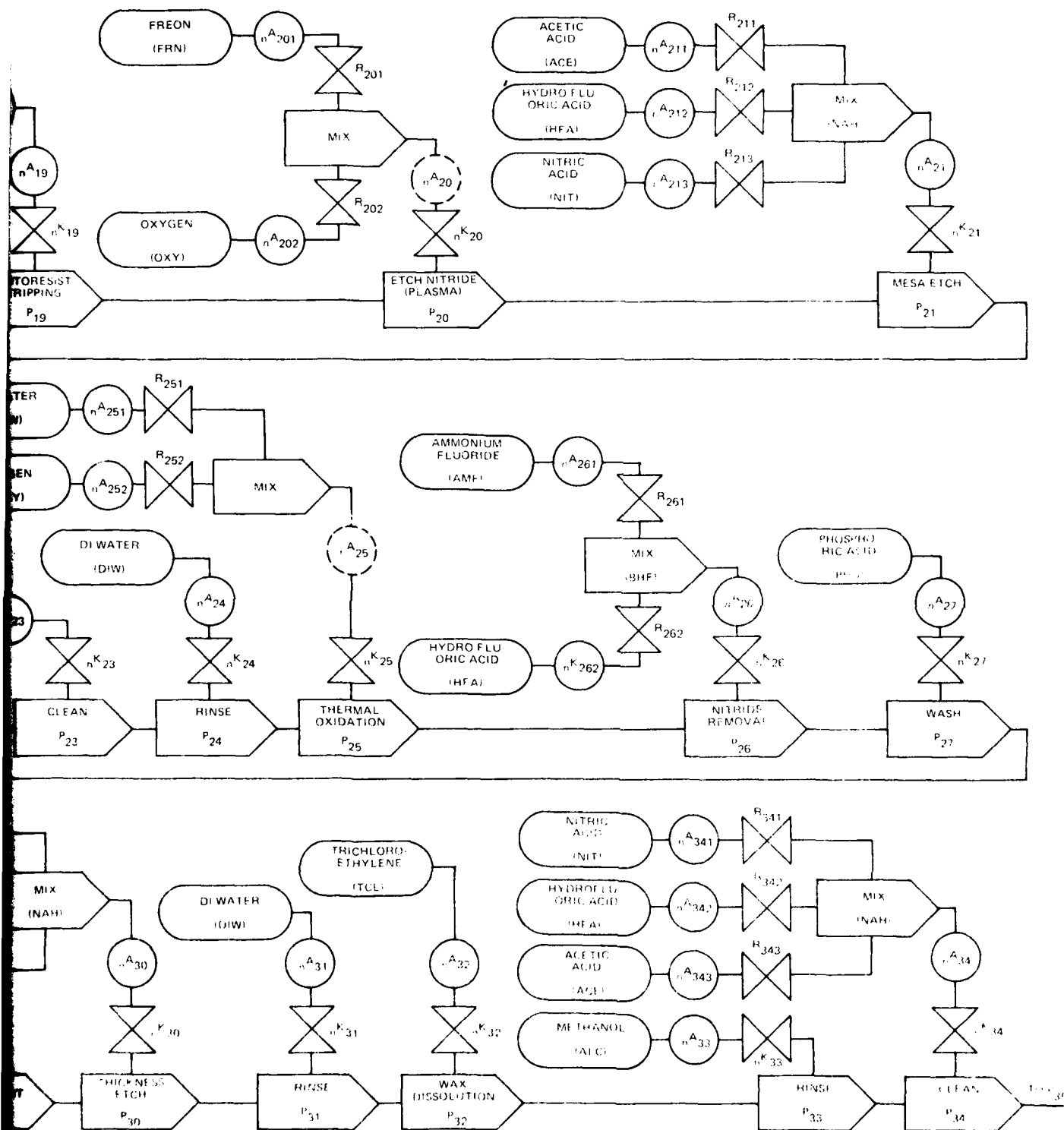
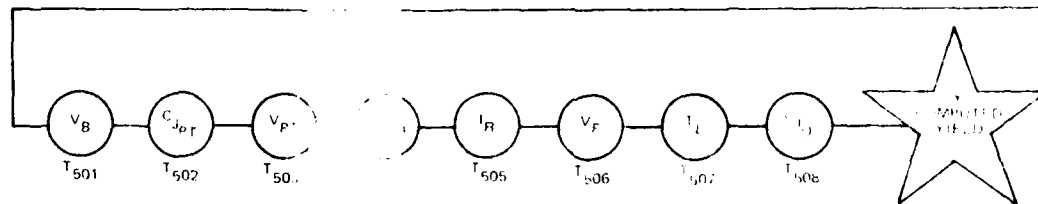
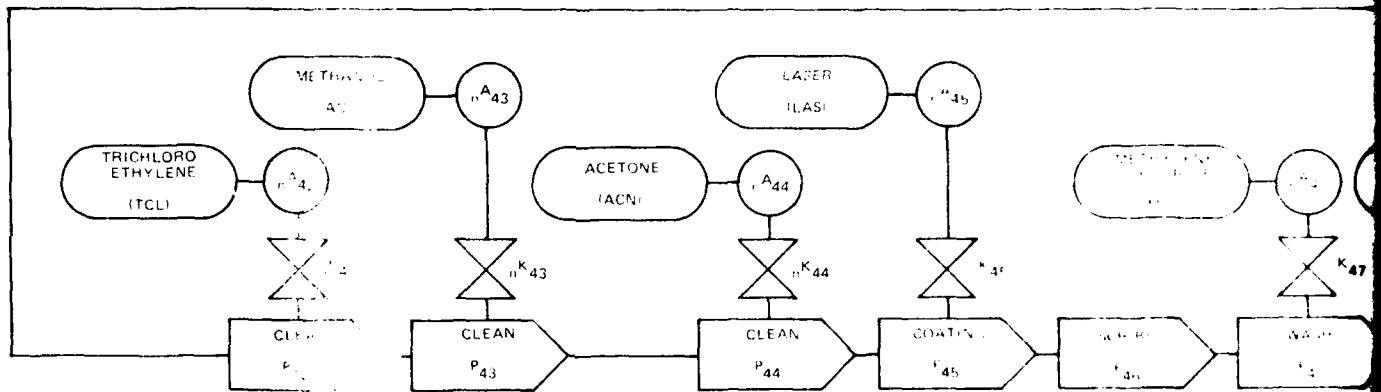
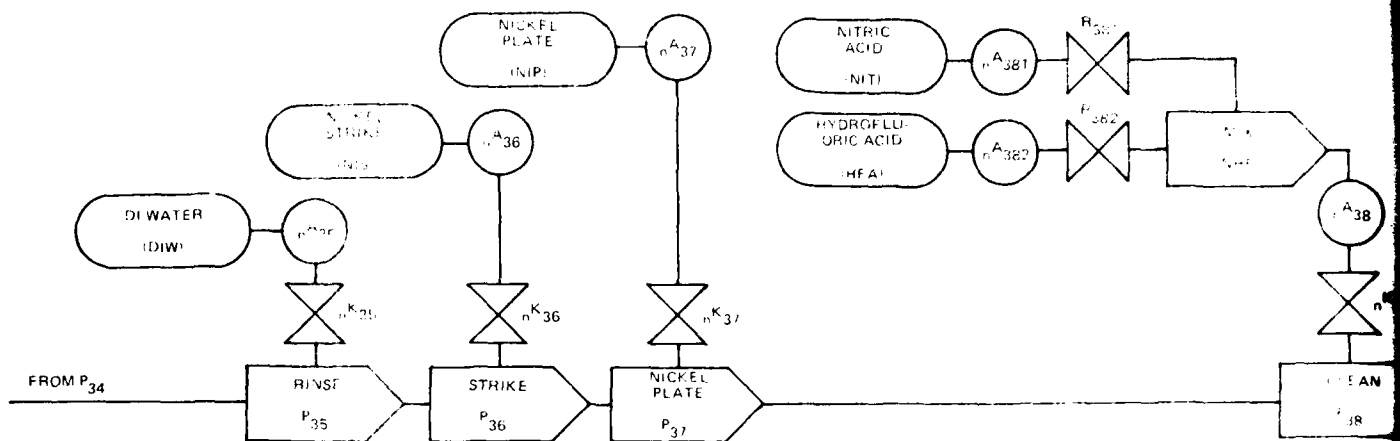
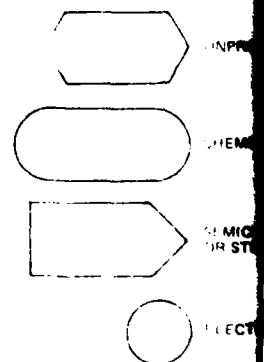


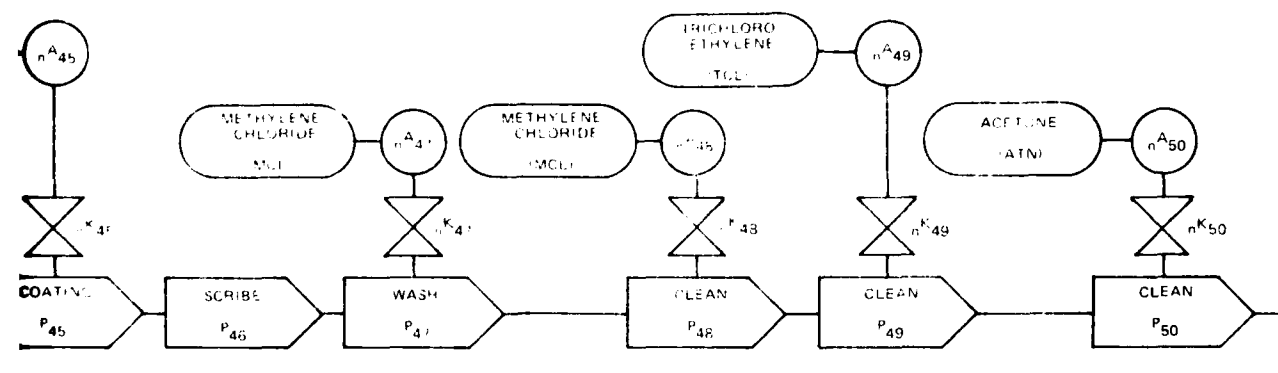
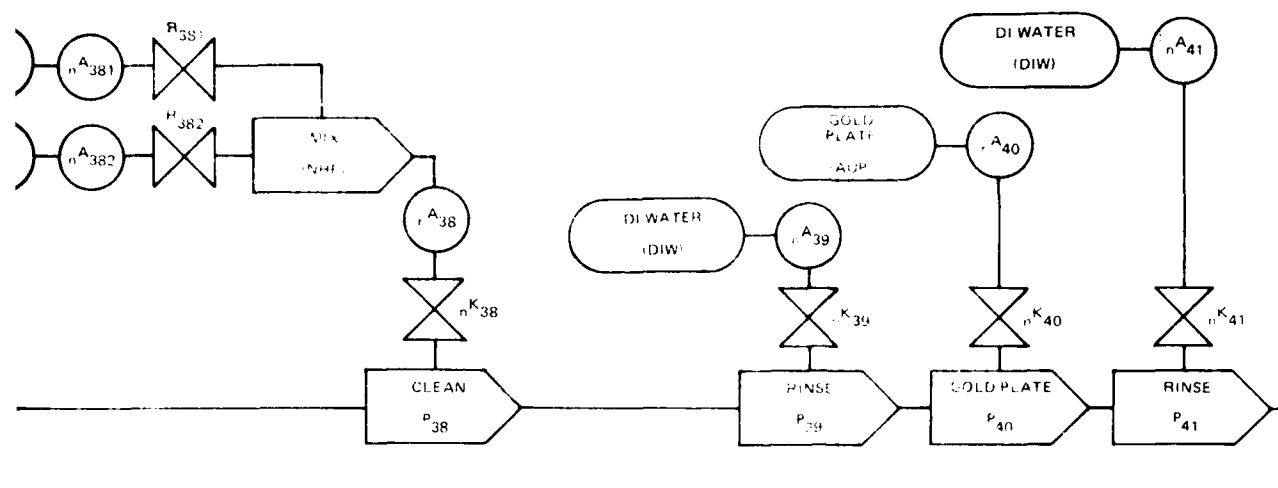
Figure 3-1. PIN Diode Manufacturing Process (Sheet 2 of 3)

3-11/3-12

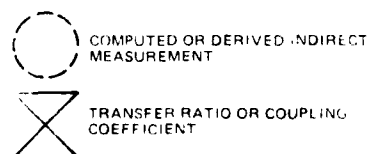
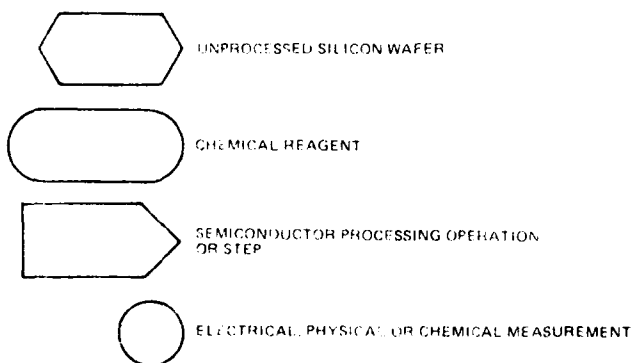


LEGEND





LEGEND



P_{XX} - PROCESS STEP IDENTIFICATION
 T_{XX} - ELECTRICAL TEST IDENTIFICATION
 A - MEASURED OR DERIVED CONTAMINANT CONCENTRATION LEVEL
 K - VALUE OF TRANSFER RATIO



Figure 3-1. PIN Diode Manufacturing Process (Sheet 3 of 3)

WATER-ID	STATIONS									
	UP-LINE					DOWN-LINE				
	1	2	3	4	5	6	7	8	9	10
602510.06	123450	184012	345678	401234	567890	123456	789012	543210	901234	567890
602510.07	XXXXXX	XXXXXX	X.XX.X	X.XX.	X.XX.	.....	.....	.....	.....	.....
602510.08	XXXXXX	XXXXXX	X.XX.X	X.XX.	X.XX.	.....	.....	.....	.....	.....
602510.09	XXXXXX	XXXXXX	X.XX.X	X.XX.	X.XX.	.....	.....	.....	.....	.....
602510.10	XXXXXX	XXXXXX	X.XX.X	X.XX.	X.XX.	.....	.....	.....	.....	.....
602610.01	XXXXXX	XXXXXX	X.XX.X	X.XX.	X.XX.	.....	.....	.....	.....	.....
602610.02	XXXXXX	XXXXXX	X.XX.X	X.XX.	X.XX.	.....	.....	.....	.....	.....
602610.03	XXXXXX	XXXXXX	X.XX.X	X.XX.	X.XX.	.....	.....	.....	.....	.....
602610.04	XXXXXX	XXXXXX	X.XX.X	X.XX.	X.XX.	.....	.....	.....	.....	.....
602610.05	XXXXXX	XXXXXX	X.XX.X	X.XX.	X.XX.	.....	.....	.....	.....	.....
602610.06	XXXXXX	XXXXXX	X.XX.X	X.XX.	X.XX.	.....	.....	.....	.....	.....
602610.07	XXXXXX	XXXXXX	X.XX.X	X.XX.	X.XX.	.....	.....	.....	.....	.....
602610.08	XXXXXX	XXXXXX	X.XX.X	X.XX.	X.XX.	.....	.....	.....	.....	.....
602610.09	XXXXXX	XXXXXX	X.XX.X	X.XX.	X.XX.	.....	.....	.....	.....	.....
602610.10	XXXXXX	XXXXXX	X.XX.X	X.XX.	X.XX.	.....	.....	.....	.....	.....

END OF CHEMICAL DATA

Figure 3-2. Sheet 4 of 8

ELECTRICAL STAPLERS

	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17		18		19		20		21		22		23		24		25		26		27		28		29		30		31		32		33		34		35		36		37		38		39		40		41		42		43		44		45		46		47		48		49		50		51		52		53		54		55		56		57		58		59		60		61		62		63		64		65		66		67		68		69		70		71		72		73		74		75		76		77		78		79		80		81		82		83		84		85		86		87		88		89		90		91		92		93		94		95		96		97		98		99		100		101		102		103		104		105		106		107		108		109		110		111		112		113		114		115		116		117		118		119		120		121		122		123		124		125		126		127		128		129		130		131		132		133		134		135		136		137		138		139		140		141		142		143		144		145		146		147		148		149		150		151		152		153		154		155		156		157		158		159		160		161		162		163		164		165		166		167		168		169		170		171		172		173		174		175		176		177		178		179		180		181		182		183		184		185		186		187		188		189		190		191		192		193		194		195		196		197		198		199		200		201		202		203		204		205		206		207		208		209		210		211		212		213		214		215		216		217		218		219		220		221		222		223		224		225		226		227		228		229		230		231		232		233		234		235		236		237		238		239		240		241		242		243		244		245		246		247		248		249		250		251		252		253		254		255		256		257		258		259		260		261		262		263		264		265		266		267		268		269		270		271		272		273		274		275		276		277		278		279		280		281		282		283		284		285		286		287		288		289		290		291		292		293		294		295		296		297		298		299		300		301		302		303		304		305		306		307		308		309		310		311		312		313		314		315		316		317		318		319		320		321		322		323		324		325		326		327		328		329		330		331		332		333		334		335		336		337		338		339		340		341		342		343		344		345		346		347		348		349		350		351		352		353		354		355		356		357		358		359		360		361		362		363		364		365		366		367		368		369		370		371		372		373		374		375		376		377		378		379		380		381	
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Figure 3-2. Sheet 5 of 8

602010.04
602010.05
602010.06
602010.07
602010.08
602010.09
602010.10
602110.01
602110.02
602110.03
602110.04
602110.05
602110.06
602110.07
602110.08
602110.09
602110.10
602210.01
602210.02
602210.03
602210.04
602210.05
602210.06
602210.07
602210.08
602210.09
602210.10
602310.01
602310.02
602310.03
602310.04
602310.05
602310.06
602310.07
602310.08
602310.09
602310.10
602410.01
602410.02
602410.03
602410.04
602410.05
602410.06
602410.07
602410.08
602410.09
602410.10
602510.01
602510.02
602510.03
602510.04

[illegible]

Figure 3-2. Sheet 7 of 8

WAFEN-1115

602510.025
602510.04
602510.05
602510.06
602510.07
602510.08
602510.09
602510.10
602610.01
602610.02
602610.03
602610.04
602610.05
602610.06
602610.07
602610.08
602610.09
602610.10

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OFFICE OF THE CHIEF OF STAFF
WASHINGTON, D.C. 20315

SECRET

ELECTRICAL STATIONS

[illegible]

Figure 3-2. Sheet 8 of 8

There are three file structures which were essential to the Chemical Analysis database: the transmitted data files, the stored data file, and the index file (see Figure 3-3).

When data was transmitted from Microwave Associates it was entered into a FIELDATA file which was identified by the data of transmission and a letter appended to the date indicating its sequence during that day, e.g., U7AUG780 was the third file transmitted on Aug. 7, 1978. These files include data for particular wafers at particular stations.

After data was transmitted it was then checked for integrity by the TRANDATA program (see Section 3.4), which stored consistent data in the storage file COMBO. This step was necessary in order to build an ensemble of data for each wafer from the discrete records available in the transmitted file.

The index file HEADER associated with each wafer and station a record number at which the data for that wafer and station was located.

3.4 COMPUTER PROGRAMS DEVELOPED AND UTILIZED

Data analysis was performed essentially through use of the BIOMEDICAL COMPUTER PROGRAMS of the UNIVERSITY OF CALIFORNIA AT LOS ANGELES (BMOP) statistical package. The programs from this package which were used in the analyses were:

- P5D - Histograms and Univariate Plots
- P6D - Bivariate (Scatter) Plots
- P1M - Cluster Analysis of Variables
- P4M - Factor Analysis
- P6M - Canonical Correlation Analysis
- P1R - Multiple Linear Regression
- P6R - Partial Correlation and Multivariate Regression

In addition several utility programs were developed in FORTRAN IV to aid in the storage, analysis, and retrieval of data from the database:

- o NEWSCAN allowed editing of the data transmitted from Microwave Associates before processing to facilitate correction of transmission errors;

DATA FILE

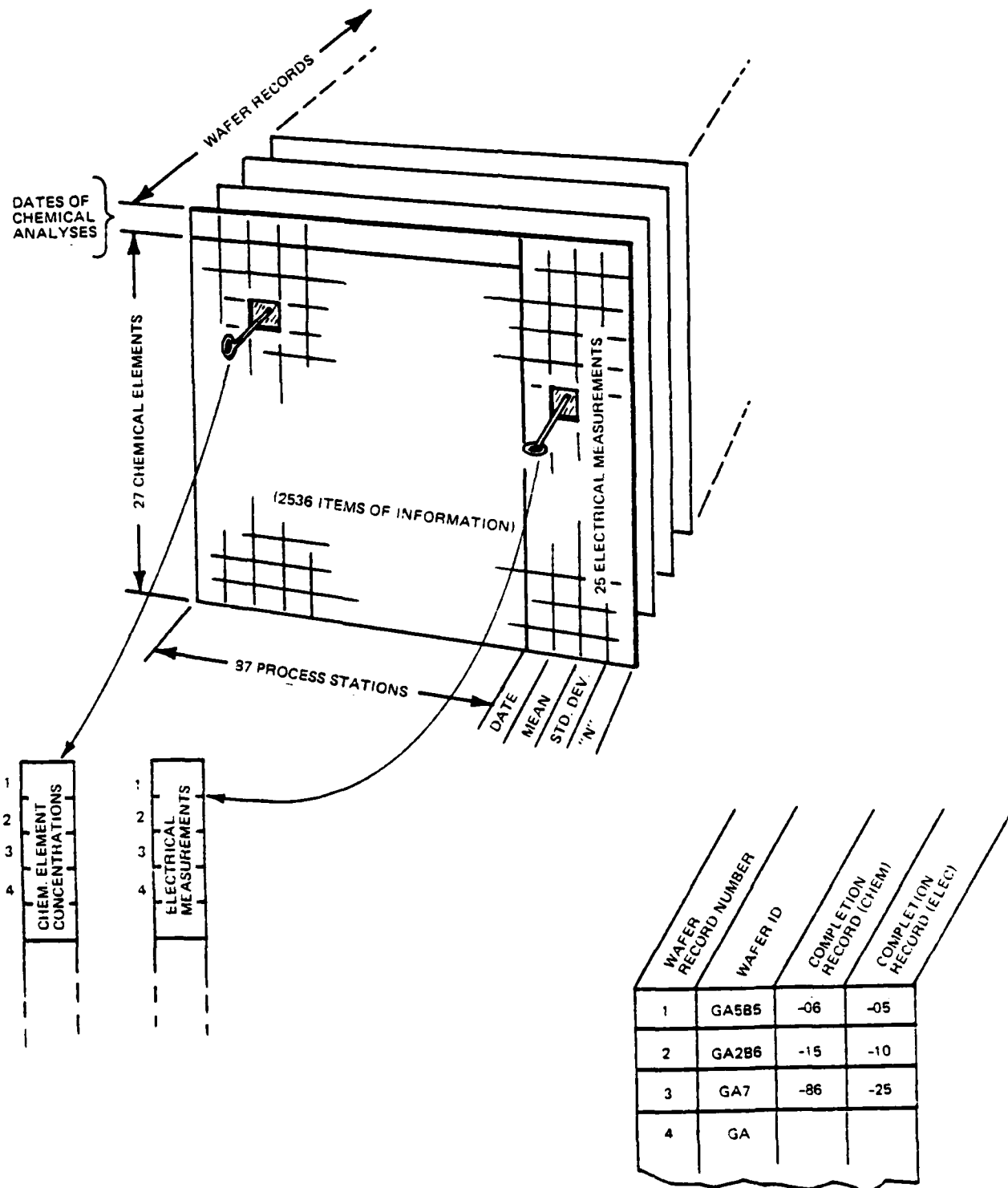


Figure 3-3. Data File

WAFER
DATA LCG

- o TRANDATA compared the triplicate records transmitted from Microwave Associates to PRD Electronics, verified the integrity of the transmission, stored consistent data in the database, and updated the index files;
- o EXDOT/500 produced the schmoo which is a record of the contemporary state of the database;
- o INSTAT enabled selection of any particular item in the database for entry into a standard formatted file;
- o COMPOSITE built composite scores for contaminants monitored at each of the 50 stations from their individual values.

Complete listings for these utility programs are included in listing 1 of the archive (see Table 3-1).

To enable efficient execution of the BMDP programs Job Control Language batch streams were constructed for each particular program to execute that analysis for each of the 50 stations and each of the 27 contaminants.

TABLE 3-1. LISTINGS INCLUDED IN ARCHIVES

1 - Utility Programs
2 - Histograms for LITHIUM throughout PIN diode process
3 - Histograms for COPPER throughout PIN diode process
4 - Histograms for MAGNESIUM throughout PIN diode process
5 - Histograms for CADMIUM throughout PIN diode process
6 - Histograms for BORON throughout PIN diode process
7 - Histograms for GERMANIUM throughout PIN diode process
8 - Histograms for PHOSPHORUS throughout PIN diode process
9 - Histograms for CHROMNIUM throughout PIN diode process
10 - Histograms for IRON throughout PIN diode process
11 - Histograms for SODIUM throughout PIN diode process

TABLE 3-1. LISTINGS INCLUDED IN ARCHIVES (Contd)

12 - Histograms for SILVER throughout PIN diode process
13 - Histograms for CALCIUM throughout PIN diode process
14 - Histograms for MERCURY throughout PIN diode process
15 - Histograms for ALUMINUM throughout PIN diode process
16 - Histograms for TIN throughout PIN diode process
17 - Histograms for ARSENIC throughout PIN diode process
18 - Histograms for MOLYBDENUM throughout PIN diode process
19 - Histograms for COBALT throughout PIN diode process
20 - Histograms for POTASSIUM throughout PIN diode process
21 - Histograms for GOLD throughout PIN diode process
22 - Histograms for ZINC throughout PIN diode process
23 - Histograms for PALLADIUM throughout PIN diode process
24 - Histograms for GALLIUM throughout PIN diode process
25 - Histograms for LEAD throughout PIN diode process
26 - Histograms for ANTIMONY throughout PIN diode process
27 - Histograms for MANGANESE throughout PIN diode process
28 - Histograms for NICKEL throughout PIN diode process
29 - Scatter Plots for WSH01 vs. final electrical measurements
30 - Scatter Plots for DIP02 vs. final electrical measurements
31 - Scatter Plots for CLE03 vs. final electrical measurements
32 - Scatter Plots for RIN04 vs. final electrical measurements
33 - Scatter Plots for BDE05 vs. final electrical measurements
34 - Scatter Plots for BDI06 vs. final electrical measurements
35 - Scatter Plots for BRE07 vs. final electrical measurements
36 - Scatter Plots for ETC08 vs. final electrical measurements
37 - Scatter Plots for RIN09 vs. final electrical measurements
38 - Scatter Plots for DIP10 vs. final electrical measurements
39 - Scatter Plots for RIN11 vs. final electrical measurements
40 - Scatter Plots for DSN12 vs. final electrical measurements
41 - Scatter Plots for NDE13 vs. final electrical measurements
42 - Scatter Plots for PHA14 vs. final electrical measurements
43 - Scatter Plots for RIN15 vs. final electrical measurements
44 - Scatter Plots for PHD16 vs. final electrical measurements
45 - Scatter Plots for ETC17 vs. final electrical measurements

TABLE 3-1. LISTINGS INCLUDED IN ARCHIVES (Contd)

46 - Scatter Plots for RIN18 vs. final electrical measurements
47 - Scatter Plots for PHS19 vs. final electrical measurements
48 - Scatter Plots for ETN20 vs. final electrical measurements
49 - Scatter Plots for MES21 vs. final electrical measurements
50 - Scatter Plots for RIN22 vs. final electrical measurements
51 - Scatter Plots for CLE23 vs. final electrical measurements
52 - Scatter Plots for RIN24 vs. final electrical measurements
53 - Scatter Plots for THO25 vs. final electrical measurements
54 - Scatter Plots for NIR26 vs. final electrical measurements
55 - Scatter Plots for WSH27 vs. final electrical measurements
56 - Scatter Plots for RIN28 vs. final electrical measurements
57 - Scatter Plots for WXE29 vs. final electrical measurements
58 - Scatter Plots for THE30 vs. final electrical measurements
59 - Scatter Plots for RIN31 vs. final electrical measurements
60 - Scatter Plots for WXU32 vs. final electrical measurements
61 - Scatter Plots for RIN33 vs. final electrical measurements
62 - Scatter Plots for CLE34 vs. final electrical measurements
63 - Scatter Plots for RIN35 vs. final electrical measurements
64 - Scatter Plots for STR36 vs. final electrical measurements
65 - Scatter Plots for NIP37 vs. final electrical measurements
66 - Scatter Plots for CLE38 vs. final electrical measurements
67 - Scatter Plots for RIN39 vs. final electrical measurements
68 - Scatter Plots for AUP40 vs. final electrical measurements
69 - Scatter Plots for RIN41 vs. final electrical measurements
70 - Scatter Plots for CLE42 vs. final electrical measurements
71 - Scatter Plots for CLE43 vs. final electrical measurements
72 - Scatter Plots for CLE44 vs. final electrical measurements
73 - Scatter Plots for COT45 vs. final electrical measurements
74 - Scatter Plots for WSH47 vs. final electrical measurements
75 - Scatter Plots for CLE48 vs. final electrical measurements
76 - Scatter Plots for CLE49 vs. final electrical measurements
77 - Scatter Plots for CLE50 vs. final electrical measurements

TABLE 3-1. LISTINGS INCLUDED IN ARCHIVES (Contd)

78	- Partial Correlations and Multivariate Regression for LITHIUM
79	- Partial Correlations and Multivariate Regression for COPPER
80	- Partial Correlations and Multivariate Regression for MAGNESIUM
81	- Partial Correlations and Multivariate Regression for CADMIUM
82	- Partial Correlations and Multivariate Regression for BORON
83	- Partial Correlations and Multivariate Regression for GERMANIUM
84	- Partial Correlations and Multivariate Regression for PHOSPHORUS
85	- Partial Correlations and Multivariate Regression for CHROMNIUM
86	- Partial Correlations and Multivariate Regression for IRON
87	- Partial Correlations and Multivariate Regression for SODIUM
88	- Partial Correlations and Multivariate Regression for SILVER
89	- Partial Correlations and Multivariate Regression for CALCIUM
90	- Partial Correlations and Multivariate Regression for MERCURY
91	- Partial Correlations and Multivariate Regression for ALUMINUM
92	- Partial Correlations and Multivariate Regression for TIN
93	- Partial Correlations and Multivariate Regression for ARSENIC
94	- Partial Correlations and Multivariate Regression for MOLYBDENUM
95	- Partial Correlations and Multivariate Regression for COBALT
96	- Partial Correlations and Multivariate Regression for POTASSIUM
97	- Partial Correlations and Multivariate Regression for GOLD

TABLE 3-1. LISTINGS INCLUDED IN ARCHIVES (Contd)

98	- Partial Correlations and Multivariate Regression for ZINC
99	- Partial Correlations and Multivariate Regression for PALLADIUM
100	- Partial Correlations and Multivariate Regression for GALLIUM
101	- Partial Correlations and Multivariate Regression for LEAD
102	- Partial Correlations and Multivariate Regression for ANTIMONY
103	- Partial Correlations and Multivariate Regression for MANGANESE
104	- Partial Correlations and Multivariate Regression for NICKEL
105	- Partial Correlations and Multivariate Regression for WSH01
106	- Partial Correlations and Multivariate Regression for DIP02
107	- Partial Correlations and Multivariate Regression for CLE03
108	- Partial Correlations and Multivariate Regression for RIN04
109	- Partial Correlations and Multivariate Regression for BDE05
110	- Partial Correlations and Multivariate Regression for BDI06
111	- Partial Correlations and Multivariate Regression for BRE07
112	- Partial Correlations and Multivariate Regression for ETC08
113	- Partial Correlations and Multivariate Regression for RIN09
114	- Partial Correlations and Multivariate Regression for DIP10
115	- Partial Correlations and Multivariate Regression for RIN11
116	- Partial Correlations and Multivariate Regression for DSN12
117	- Partial Correlations and Multivariate Regression for NDE13
118	- Partial Correlations and Multivariate Regression for PHA14
119	- Partial Correlations and Multivariate Regression for RIN15
120	- Partial Correlations and Multivariate Regression for PHD16
121	- Partial Correlations and Multivariate Regression for ETC17
122	- Partial Correlations and Multivariate Regression for RIN18
123	- Partial Correlations and Multivariate Regression for PHS19
124	- Partial Correlations and Multivariate Regression for ETN20
125	- Partial Correlations and Multivariate Regression for MES21
126	- Partial Correlations and Multivariate Regression for RIN22
127	- Partial Correlations and Multivariate Regression for CLE23

TABLE 3-1. LISTINGS INCLUDED IN ARCHIVES (Contd)

128	- Partial Correlations and Multivariate Regression for RIN24
129	- Partial Correlations and Multivariate Regression for THO25
130	- Partial Correlations and Multivariate Regression for NIR26
131	- Partial Correlations and Multivariate Regression for WSH27
132	- Partial Correlations and Multivariate Regression for RIN28
133	- Partial Correlations and Multivariate Regression for WXE29
134	- Partial Correlations and Multivariate Regression for THE30
135	- Partial Correlations and Multivariate Regression for RIN31
136	- Partial Correlations and Multivariate Regression for WXU32
137	- Partial Correlations and Multivariate Regression for RIN33
138	- Partial Correlations and Multivariate Regression for CLE34
139	- Partial Correlations and Multivariate Regression for RIN35
140	- Partial Correlations and Multivariate Regression for STR36
141	- Partial Correlations and Multivariate Regression for NIP37
142	- Partial Correlations and Multivariate Regression for CLE38
143	- Partial Correlations and Multivariate Regression for RIN39
144	- Partial Correlations and Multivariate Regression for AUP40
145	- Partial Correlations and Multivariate Regression for RIN41
146	- Partial Correlations and Multivariate Regression for CLE42
147	- Partial Correlations and Multivariate Regression for CLE43
148	- Partial Correlations and Multivariate Regression for CLE44
149	- Partial Correlations and Multivariate Regression for COT45
150	- Partial Correlations and Multivariate Regression for WSH47
151	- Partial Correlations and Multivariate Regression for CLE48
152	- Partial Correlations and Multivariate Regression for CLE49
153	- Partial Correlations and Multivariate Regression for CLE50
154	- Factor Analysis Station WSH01
155	- Factor Analysis Station DIP02
156	- Factor Analysis Station CLE03
157	- Factor Analysis Station RIN04
158	- Factor Analysis Station BDE05
159	- Cluster Analyses
160	- Canonical Correlations

3.5 STATISTICAL METHODS

The following analyses were performed on the database using BMDP programs in conjunction with the utility programs and JCL batch streams described in the preceeding section:

HISTOGRAMS AND UNIVARIATE PLOTS
SCATTER PLOTS
CLUSTER ANALYSIS
FACTOR ANALYSIS
CANONICAL CORRELATION ANALYSIS
PARTIAL CORRELATION AND MULTIVARIATE REGRESSION
MULTIPLE LINEAR REGRESSION

A brief description of the methods employed in these analyses and any conclusions ascertained follows. For a more comprehensive treatment of the methods the reader may refer to Appendix B. In addition, complete listings of all significant analyses performed are included in the accompanying archives. These archives are indexed in Table 3-1.

Histograms of the frequency distribution and of the cumulative distribution function for each variable were constructed to provide a basic pictorial description of the database (see Figure 3-4). The frequency distribution and cumulative distribution were printed beside each histogram, both as frequencies and percentages. Normal and half-normal probability plots were used to screen the data for nonnormality or the presence of outliers. Cumulative frequencies versus data values were also printed. Finally the frequency, mean and standard deviation were indicated for each item.

Scatter plots of the level of impurity for each element at each station versus yield were performed to explore possible linear or nonlinear relationships as well as tabulate the correlation of each element with the yield. Equations of the simple

linear regressions relating each variable to the other were computed and printed and the intersections of the regression lines with the frame of the plot were indicated (see Figure 3-5). No significant relationships were found between the presence of impurities at a particular station and the final yield of the wafer. A complete record of the correlation coefficient for the level of each contaminant at each station with each of the electrical measurements comprising the final yield is contained in the tables in Appendix C.

In order to bring the problem down to size an attempt was made to use cluster analysis to group variables to be used in predictability analyses. Clusters of variables based on a measure of association or similarity between the variables and on a measure of the distance separating variables were formed according to specified linkage algorithms. The linkage rule determines the similarity of any two clusters of variables. Initially each variable is considered a cluster that contains one variable only. At each step the two most similar clusters are joined to form a new cluster, until a single cluster is obtained that contains all the variables. However, no clustering which would effectively reduce the scope of the problem was indicated.

Another methodology employed to reduce the scope of the problem was factor analysis. Initial factor extraction was performed by principal components, maximum likelihood, Kaiser's Second Generation Little Jiffy, and iterated principal factor analysis. Several methods of rotation were attempted: varimax, direct quartimin, and orthogonal. Mahalanobis distances were computed from the centroid of all cases for the factor scores, original data, and the residuals of original data regressed on the factor scores (see Figure 3-6). Nonetheless, because the ratio of variables to number of experiments was too large no significant results were forthcoming.

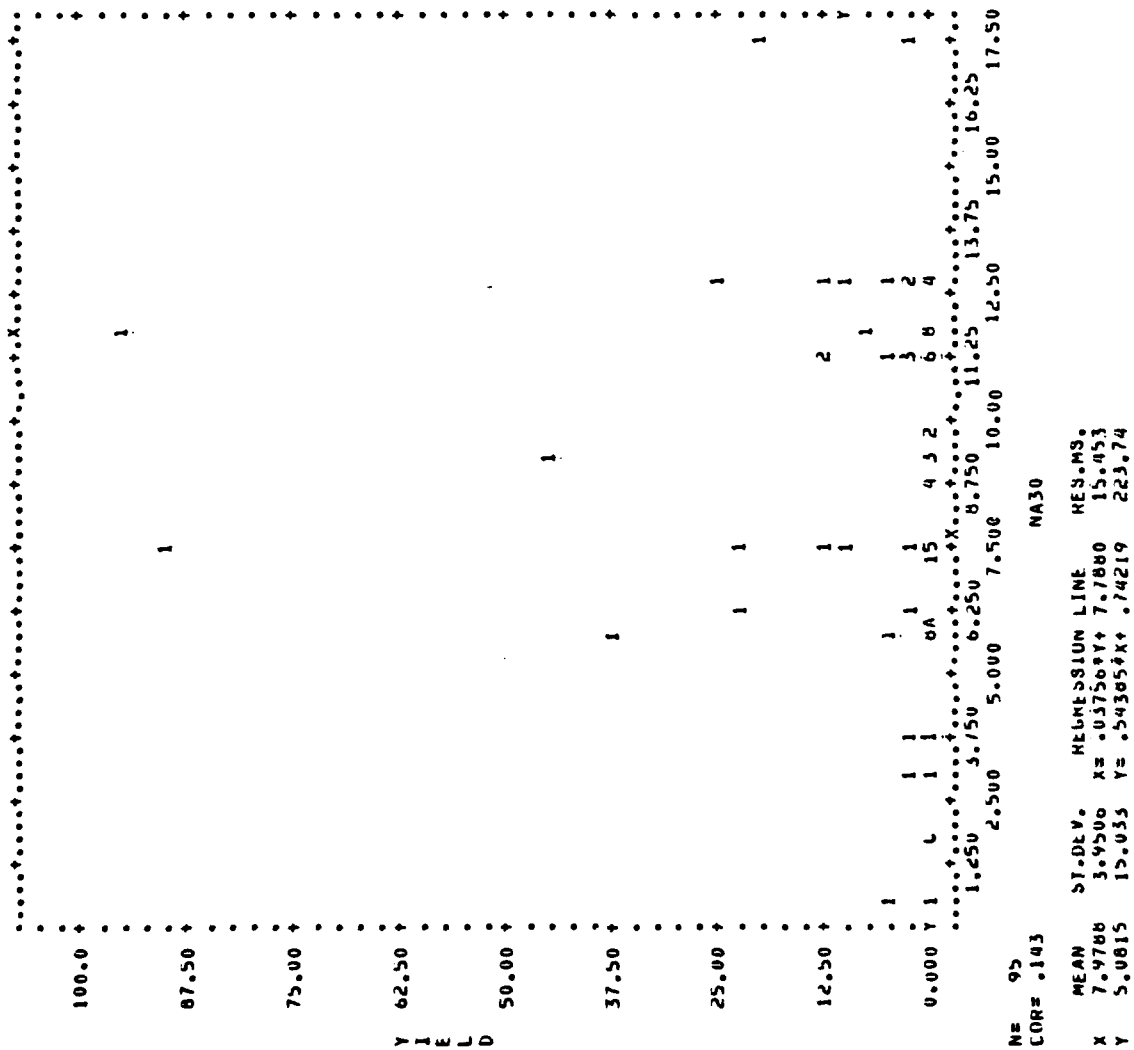


Figure 3-5. Scatter plot for Lithium Vs. Yield

UNROTATED FACTOR LOADINGS (PATTERNS)
FOR PRINCIPAL COMPONENTS

	FACTOR 1	FACTOR 2	FACTOR 3	FACTOR 4	FACTOR 5	FACTOR 6	FACTOR 7	FACTOR 8	FACTOR 9
LI05	.045	-.104	.076	-.314	-.315	.024	-.064	.115	-.122
LI05	.455	-.174	.265	-.497	.404	-.304	-.245	.070	-.041
MA05	.455	.525	.201	-.443	-.443	.205	.102	-.070	-.011
CU05	.384	-.064	-.822	-.211	.069	.132	-.016	.040	.150
BO5	.074	.947	.034	-.041	.216	-.069	.011	.071	.058
BE05	.742	-.068	.357	.063	-.069	.120	.140	.053	.053
PO5	.620	-.045	-.104	.458	-.203	.277	-.142	.103	.152
CR05	.407	.010	.033	.274	.186	.030	-.002	-.131	.002
FE05	.654	-.111	-.170	.480	.545	.088	.004	-.208	-.014
MA05	.543	-.162	.109	-.263	-.050	-.228	.561	.061	.124
AG05	.427	-.107	.104	.036	.236	-.052	-.060	-.094	.052
CA05	.873	.049	.205	.154	-.005	-.015	.275	-.124	.140
HG05	.516	-.371	.177	.264	.404	-.129	-.131	.055	.283
AL05	.793	-.153	.060	-.338	-.081	-.064	.344	-.023	.184
SN05	.784	.123	-.184	-.137	-.379	.039	-.011	.019	-.122
AS05	.644	-.146	.004	.657	-.080	-.124	.003	.476	-.220
MO05	.776	.538	.064	-.031	.016	.012	-.061	.084	-.121
CO05	.832	-.049	.078	-.358	-.286	.005	-.068	.119	-.105
K05	.825	-.100	.068	-.411	-.260	.002	-.047	.100	-.072
AU05	.886	-.014	-.073	.401	.133	.066	.024	-.034	-.024
ZN05	-.043	-.010	.001	.125	.120	-.104	.051	.750	-.073
PU05	.854	.124	.103	-.013	-.337	.085	-.102	.072	-.185
GA05	.867	.158	.020	.365	.159	-.043	.041	-.107	-.084
PR05	.947	.947	.020	-.045	.217	-.066	.011	.072	.061
SB05	.945	-.182	-.003	.086	.145	-.062	-.064	-.045	-.108
MN05	.382	.634	.042	-.074	.324	-.114	-.044	.048	.045
NI05	.495	-.182	.271	-.439	.414	-.306	-.300	.061	-.057
TS01	.006	.287	.546	.109	-.342	.015	-.114	.044	.424
TS02	-.174	-.278	.593	-.183	.219	.466	-.004	.003	.007
TS03	-.007	.468	-.044	-.029	.299	.292	.230	-.068	.165
TS04	-.398	-.067	.766	.158	.049	.203	.017	-.047	.118
TS05	-.188	-.121	-.058	-.021	.123	.203	.763	.066	-.014
TS06	-.430	.018	.793	.161	-.073	-.187	.096	-.023	-.166
TS07	-.043	-.042	.047	.047	.008	.212	-.178	.308	.652
TS08	.107	-.070	-.029	-.446	.307	.741	.058	.050	.036
YIELD	-.095	.130	-.071	.048	-.288	-.448	-.335	-.334	.216
VP	12.447	3.916	3.074	2.771	2.207	1.766	1.603	1.228	1.195

THE VP FOR EACH FACTOR IS THE SUM OF THE SQUARES OF THE ELEMENTS OF THE COLUMN OF THE FACTOR LOADING MAINLY CORRESPONDING TO THAT FACTOR. THE VP IS THE VARIANCE EXPLAINED BY THE FACTOR.

Figure 3-6. Unrotated Factor Loadings (Pattern) for Principal Components

Canonical correlation analysis was performed between the chemical impurities at each station and the final electrical measurements and between the level of impurity of an element at all stations and the final electrical measurements. Canonical correlations, coefficients for the canonical variables, canonical variable scores, and the canonical variable loadings were computed (see Figure 3-7). The eigenvalues associated with each pair of canonical variables and Bartlett's test for the significance of the remaining eigenvalues were calculated. Again, no significant canonical correlations were found.

Partial correlations and multivariate regression were computed for the yield and the level of impurity of an element at all stations and for the yield and the chemical impurities at a particular station. This analysis calculated the partial correlations, regression coefficients and their standard errors, squared multiple correlations, and residuals for the data (see Figure 3-8). Significance tests performed failed to show any significant correlation or predictable regression.

The multiple linear regression equations using the yield as the dependent variable and the level of impurity of an element at all stations as the independent variables or the chemical impurities at a particular station as the independent variables were estimated. These equations were not useful in predictability analysis because significance tests failed.

In order to perform any significant analyses on the data the number of independent variables must be reduced or the number of experiments increased. Since no control exists over the latter, any future attempts to analyze the data must focus on the former. However, an approach must be formulated to intelligently reduce the number of variables since random reduction is senseless in view of the large number of them. We have not been successful in discovering such an approach, in spite of the many statistical tools employed in the effort.

CANONICAL VARIABLE LOADINGS (CORRELATIONS OF CANONICAL VARIABLES WITH ORIGINAL VARIABLES)

	CNVF1	CNVF2	CNVF3	CNVF4	CNVF5	CNVF6	CNVF7	CNVF8
1501	.28	.180	-.351	.701	-.224	-.233	.180	.447
1502	29	.763	.466	.255	-.256	.097	.053	.013
1503	30	-.364	.070	.318	-.029	.632	-.566	.181
1504	31	.534	.355	.610	.456	.030	-.030	.030
1505	32	-.305	.679	-.054	-.004	-.495	-.375	.232
1506	33	.085	.468	.685	.301	-.039	.445	.005
1507	34	-.064	-.115	.067	-.050	-.103	-.020	-.178
1508	35	.502	.169	-.268	-.360	.584	-.263	.165

	CNVF1	CNVF2	CNVF3	CNVF4	CNVF5	CNVF6	CNVF7	CNVF8
1122	1	.003	.344	.048	.283	-.076	-.077	.065
1022	2	-.137	-.227	.197	-.097	.402	.192	.192
1022	3	-.468	.431	-.068	-.003	.297	-.070	-.125
1022	4	.132	-.479	-.110	-.012	-.076	.141	.449
1022	5	.244	-.375	.088	.062	-.042	.209	-.386
1022	6	.354	-.119	.105	-.099	-.098	-.235	.068
1022	7	.092	-.140	.164	-.027	.334	.208	.197
1022	8	.076	-.103	.169	-.039	.319	.251	-.192
1022	9	.076	-.139	.186	-.021	.315	.256	-.237
1022	10	-.478	.347	-.116	-.025	.292	-.336	-.109
1022	11	-.044	-.077	.019	-.212	.094	.374	.144
1022	12	-.311	-.054	-.085	.387	.356	-.228	-.297
1022	13	.436	-.018	.089	-.216	.072	.145	.257
1022	14	-.576	.166	-.072	.372	.470	.021	-.263
1022	15	-.293	-.046	-.683	-.273	.101	-.143	-.162
1022	16	-.221	-.097	.260	.109	-.321	.317	-.227
1022	17	.480	.050	.197	-.085	.052	.273	-.172
1022	18	-.002	-.536	.401	-.016	.097	.076	.485
1022	19	-.003	.208	.111	-.051	-.066	.558	-.044
1022	20	.026	.104	.149	-.052	.069	.494	-.109
1022	21	.085	-.133	.152	.065	-.222	.287	-.212
1022	22	-.076	-.466	-.067	.056	-.019	.123	-.546
1022	23	-.596	.238	.127	-.271	.048	-.444	-.211
1022	24	.096	-.158	.140	-.030	.355	.186	-.176
1022	25	.177	-.309	.224	-.122	.327	.106	.234
1022	26	.051	-.136	.033	-.102	.237	.394	-.166
1022	27	.086	-.096	.164	-.024	.313	.254	-.179

PROBLEM NUMBER 1 COMPLETED.

Figure 3-7. Canonical Variable (Loadings)

SQUARED MULTIPLE CORRELATIONS OF EACH INDEPENDENT VARIABLE WITH ALL OTHER INDEPENDENT VARIABLES
(MEASURES OF MULTI-COLLINEARITY OF PREDICTOR VARIABLES)

EXCEPT FOR NON-PIVOTED VARIABLES
AND TESTS OF SIGNIFICANCE OF MULTIPLE REGRESSION
DEGREES OF FREEDOM FOR F-STATISTICS ARE 6 AND 68

VARIABLE NO.	NAME	SMC	F-STATISTIC	SIGNIFICANCE (P LESS THAN)
2	CU40	.69947	20.58	.00000
4	CU40	.98817	946.64	.00000
10	NA40	.89463	90.22	.00000
13	HE40	.97456	434.11	.00000
16	AY40	.94764	205.13	.00000
21	ZN40	.89847	100.30	.00000
27	NI40	.93707	168.77	.00000

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SQUARED MULTIPLE CORRELATIONS(SMC) OF EACH DEPENDENT VARIABLE WITH THE INDEPENDENT VARIABLES
EXCEPT FOR NON-PIVOTED VARIABLES

AND TESTS OF SIGNIFICANCE OF MULTIPLE REGRESSION
DEGREES OF FREEDOM FOR F-STATISTICS ARE 7 AND 67

VARIABLE NO.	NAME	SMC	F-STATISTIC	SIGNIFICANCE (P LESS THAN)
20	T501	.23332	4.91	.01012
29	T502	.18845	2.23	.04237
30	T503	.16468	1.89	.08543
31	T504	.36490	5.50	.00005
32	T505	.07388	.76	.61966
33	T506	.44547	7.69	.00000
34	T507	.00441	.04	.99989
35	T508	.09361	.99	.44724
36	YIELD	.01763	.17	.99009

Figure 3-8. Multivariate Regression Analysis

3.6 USE OF SPECTRAL ANALYSIS

In any major program, especially of a technical nature, one naturally hopes for but expects "spin-off's" to occur; these are the unexpected side benefits of the main thrust of the program. We have seen some "spin-off's" for the semiconductor industry using this analytical tool in a production environment and would like to describe them. For example:

- o Efficiency of water purification on an element by element basis.
- o Plating solution monitoring and control.
- o Trace analysis of impurities in silicon.
- o Incoming inspection of so-called "electronic grade chemicals".
- o Trace analysis of alloys, e.g., solder pre-forms.
- o Trace analysis of GaAs substrate.
- o Organic analysis, e.g., solvents, developers, rinses.
- o Organic standards, source and make-up.

All of these tested the versatility of the emission spectrometer in the environment of an active semiconductor fabrication laboratory.

It is worthwhile to mention briefly these sub-investigations, and indicate the main findings of the analyses. Some comments will be made, then, for each of the above.

a. Water Analysis

The facility under consideration has a large number of DI water taps strung out in long recirculation loops all over the building. It was decided to monitor on a daily basis the incoming raw water as well as the DI water produced, from each of these taps. Only a method as rapid as this could handle such a task. Data were gathered over a two-month period. Plots were generated for selected elements from this data. Of particular interest were Na, Au, Cr, Fe. Sodium is an oxide former, and with silicon can become a mobile charged impurity in the silicon oxide, causing such phenomena as post-tuning drift in varactor diodes, and "mushy" breakdown voltage in all diodes; gold in a minority carrier lifetime killer, copper and iron are considered "fast diffuser" in silicon and affect lifetime, V_b , etc. (See Figure 3-9.) Observations from the data included:

- o The varying nature of the raw water supply especially for copper and iron concentrations, on a daily basis.
- o The efficiency of removal by deionizing in the order

Na > Fe > Cu > Au

sodium being the most efficiently removed. Typically 30 ppm in raw water, 5 ppb in deionizing; for gold 5 ppb in raw, and roughly the same in deionized.

- o The tracking of the concentrations, peaks and valleys, in the deionized water with variations in the raw water.

A particularly high concentration of sodium and potassium over several days although causing much concern, was rapidly eliminated when a faulty check valve was found, by process of elimination, after the very rapid analyses of several taps in the suspected area were performed.

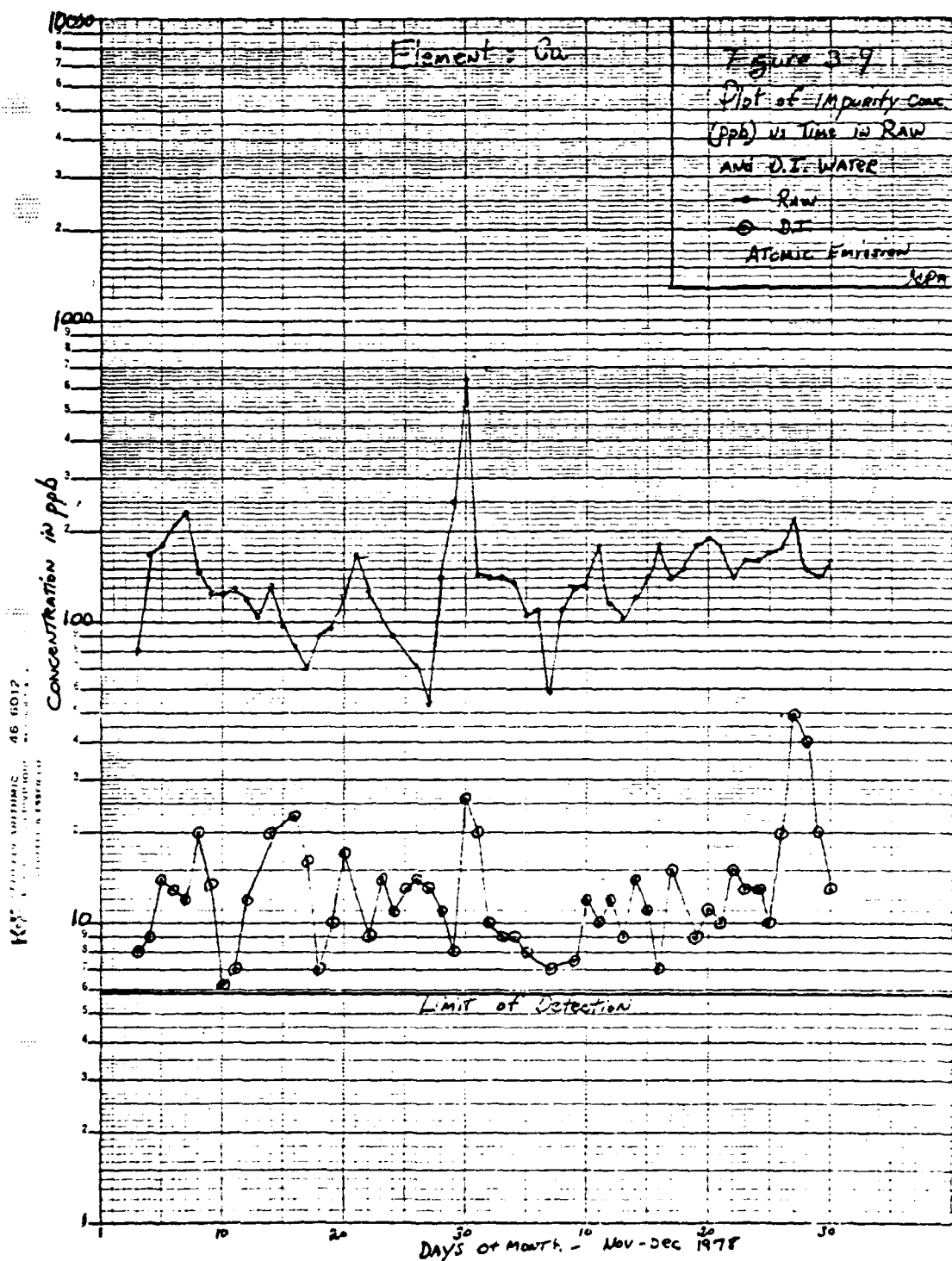


Figure 3-9. Plot of Impurity Conc. (ppb) Vs.
Time in Raw and D.I. Water

These constantly changing concentrations in the pure water might provide another source of yield problems (although a subtle source) in wafer fabrication, and until this technique with its sensitivities was applied no timely information was available. Action items based on this data were prefiltration of the raw water, bacteria removal and addition of final polishers in key locations.

b. Plating

Many plating solutions are used in a semiconductor house; these typically include gold, silver, iron, nickel, copper, and others. Plating applies to either wafer fabrication or packages. It can be a costly operation, especially where precious metals are concerned, often providing the major portion of the total device manufacturing cost. In many military specifications, quality of the plate in so far as co-plated impurity percentages is defined. It is necessary to have a rapid means of analysis for these plating solutions to insure proper maintenance and composition of the plate.

We have found the emission spectrometer extremely useful in monitoring levels of iron in nickel plating, nickel in gold plating, and nickel in silver plating. Other transition metal impurities, as well as heavy metals such as lead, tin, antimony are easily monitored. These heavy metals can be leached from various solder joints, found in the makeup water or plating salts, or might be added intentionally at some level to act as brighteners.

Techniques were developed to actually handle the plating solutions through the spectrometer. Appropriate dilutions, corrections for interference of (C=N) lines, or the intense prime metal emissions had to be made. In treating these kinds of solutions did the spectrum shifter prove its value. Because of the very intense emissions, actually becoming visible directly in the plasma, automatic background correction was found to be necessary.

The value of the system was found in the fact that a rapid timely analysis could be made, and a decision as to the treatment of the solution could be formulated before a load of packages, wafers or ceramics was committed to plating. The dollar savings in simplicity of the analysis, and higher yields due to better control, was predicted to be quite significant.

c. Trace Impurities in Silicon

The technique was used on several instances to determine trace impurities of elements in silicon. Among them:

- o Hg detection in wafers after mercury probe - led to a cleaning procedure being devised to remove all traces of mercury.
- o Arsenic contamination in the intrinsic region of a thick base PIN led to location of a faulty epitaxial reactor.
- o Gold and platinum detection on wafers which had been "stripped" of metal and cleaned - allowed a determination to be made to discard these wafers before equipment could be contaminated.

d. Incoming Inspection

Freshly purchased and unopened containers of chemicals were analyzed from time to time and the most significant findings were:

- o Copper in trichloroethylene - lot was rejected and replaced - observation verified by vendor.
- o Tin in hydrogen peroxide (unstabilized) lot was rejected - particulates analyzed by energy dispersive x-ray verified observations.

The significance of these capabilities lies in the fact that we do have a handle on potential problem lots before material and resources are committed to possible contamination and incurred costs.

e. Alloys

Often times lots of solders in pre-form when melted do not wet or flow - or the wrong melting point is observed. At this point, when packaging is involved, costs can add up quickly if die-bond yields drop.

We have used the system to analyze from a composition point of view gold-germanium, gold-tin, lead tin, lead tin silver and a few others as an incoming inspection, and also from a failure analysis point of view. Appropriate methods, e.g., hydrochloric or sulfuric acid, were used to dissolve the solder preforms, and blank analysis was carried out as well as the actual analyte. After appropriate blank subtraction, compositions could be calculated from concentration data.

f. Organic solvents present a particular set of problems to this analytical tool because of the high vapor pressure at room temperature of most of these. The major impact was the locating of a reliable manufacturer of elements dissolved in organic media which could be used for standards, and the development of techniques whereby the plasma unit could couple to the aerosol of the variety of organic solvents used.

For standards manufacture, the source was Conostan, a division of Conoco, Inc., an oil company. They are located in Ponca City, Oklahoma. A copy of their product brochure is attached. After appropriate dilution of these elemental combinations, the plasma system was standardized at 1 and 5 ppm, rather than the 0 - 10 ppm used in aqueous solutions. Since the plasma emission technique is linear over a much larger range than this, extrapolation by the system to 0 ppm is easily justified. For each organic to be measured, standards were made up from the appropriate solvents: ultra-high purity trichloroethylene, xylene, methylene chloride, etc., were used for standard preparation.

Aspirating the organic solutions into a stable plasma presented its own set of problems. High vapor pressures often caused a burst of material into the plasma, causing a de-tuning effect and extinguishing the plasma. When re-ignited, a check of the standards had to be made, and after a restandardization had to be done. This problem persisted for several months. Finally, the problem was resolved by two techniques: cooling in a thermoelectric element each sample, to reduce vapor pressure; secondly rather than aspirate the samples into the chamber, a peristaltic pump was used, manufactured by Gilson (minipuls-2). This system provided a steady, non pulsed flow of solution at a rate of about 1 mil per minute, and the mist was more controlled. Power levels of 1.7 - 1.8 k watt (RF) provided the stable plasma necessary. After analysis, purging was performed with the blank ultra-pure solvent.

In summary, the side benefits from having this rapid means of production control in the wafer fabrication area could lead to significant cost savings in terms of material labor and overhead.

SECTION IV

CONCLUSIONS

The feasibility of the project's objective to predict manufacturing yields was neither established nor discredited due to the inadequacy of the database. Nonetheless, several important contributions to the process of producing semiconductor components were forthcoming. The entire PIN diode process was carefully defined and modeled and a methodology for measuring the level of contamination at various process steps was developed. This methodology further contributed to the state of the art insofar as spectral analysis was shown to be a useful tool for detecting levels of contaminations in the reagents and solutions used in the process.

The statistical analyses performed on the database yielded no significant relationships between levels of contamination and the final yield of the wafers. However, these analyses suggest that the measurement for yield developed is ineffective from a statistical point of view; the average yield for the baseline runs is not significantly different from that of the perturbed runs (see Figure 4-1), indicating a possible problem in defining yield. Subsequent studies in this area would do well to avoid this definition.

The principal shortcomings in performing statistical analyses was the inadequacy of the database. Consequently, the direction indicated for future attempts to predict yield must be to develop a methodology for actually monitoring a diode production line in order to build a sufficiently large database upon which to conduct extensive sophisticated statistical investigations. In particular, factor analysis and canonical correlation would be invaluable tools if the database were large enough for them to be employed. The focus of these analyses would be to unearth the relationship between levels of chemical contamination and the changes in electrical parameters throughout the process.

YIELD FOR BASELINE RUNS (1-10, 12, 15)

WAFER	%YIELD
600102.01	1.51
600102.02	0.30
600202.01	1.79
600202.02	0.17
600302.01	0.41
600302.02	4.40
600402.01	0.86
600402.02	0.60
600502.01	21.61
600502.02	3.20
600602.01	11.25
600602.02	12.15
600702.01	19.00
600702.02	1.40
600802.01	0.01
600802.02	0.09
600902.01	0.02
600902.02	0.01
601002.01	44.41
601002.02	0.03
601201.01	0.20
601504.01	0.52
601504.02	0.00
601504.03	0.03
601504.04	0.00

Figure 4-1. Yield for Runs 1 through 19 (Sheet 1 of 2)

YIELD FOR DOPED RUNS (11,13,14,16-19)

		RUN (60XX10.ZZ)						
		11	13	14	16	17	18	19
CONTAMINANTS		c P24	d P24	d P11	c P11	d P24	d P11	c P07
01	Li-Na-K	0.02	0.20	0.07	0.00	1.63	0.00	0.00
02	Cu-Fe-Au	4.18	0.00	25.92	0.00	0.00	90.00	0.00
03	Mg-Ca-Cd	0.00	0.32	10.24	0.00	0.00	1.14	0.00
04	Ag-Zn-Hg	0.31	96.00	3.40	0.00	0.01	0.01	0.50
05	B-Al-Ga	0.01	7.50	0.11	0.00	3.40	22.75	0.00
06	P-As-Se	0.00	0.00	4.24	0.00	1.60	10.00	0.00
07	Ge-Pb-Sn	0.02	0.00	13.50	0.00	0.01	0.04	0.00
08	Cr-Mo-Co	36.72	0.00	0.11	0.00	4.90	0.05	0.90
09	Ni-Mn-Pd	0.80	0.07	0.00	0.00	0.00	13.50	0.00
10	CONTROL	0.08	0.02	2.50	0.00	0.08	2.25	0.42
AVERAGE		4.67	11.56	6.40	0.00	1.28	15.28	0.11

Figure 4-1. Yield for Runs 1 through 19 (Sheet 2 of 2)

APPENDIX A

A.1 MICROWAVE SEMICONDUCTOR DEVICE TECHNOLOGY

A.1.1 Introduction

Semiconductor devices manufactured for use at microwave frequencies generally originate from one of three basic semiconductor materials: silicon, germanium, or the compound semiconductor, gallium arsenide. Each step of the manufacturing process, from the formation of the original crystal ingot to the final encapsulation of the device chip, affects the yield and subsequent cost of the device. Contamination is constantly a threat, entering from any of the multitude of chemical operations, physical operations, handling, ambient changes, and all other combinations which we refer to as a process sequence. It is imperative, therefore, to manufacture the device in the cleanest, most controlled, most reproducible type of environment possible.

Microwave devices most often are designed with voltage breakdown, capacitance, series resistance (including minority carrier lifetime), the capacitance-voltage slope and leakage currents as the primary considerations. In order to provide the correct combinations of the above parameters, silicon of appropriate conductivity types, resistivities and thicknesses are necessary. The usual method to accommodate this need is to epitaxially deposit silicon of desired conductivity, resistivity and thickness onto the appropriate polished silicon substrates. This procedure results from the thinness of the layer which must be achieved (e.g., 2-6 microns) and the resistivity range which can be spanned (e.g., 0.01 to > 500 ohm-cm) while retaining the crystalline perfection found in the substrate. The substrate furnishes the required mechanical strength while minimizing the series resistance of the final structure. Junction formation is accomplished by Schottky barrier metallization or by p-n junction formation by diffusion or ion implantation.

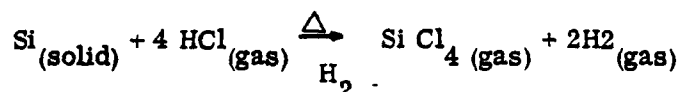
The operational function of a device, whether it be a PIN diode, a varactor, or a microwave transistor, depends on controlling impurities of known type (both donors and acceptors) as to their concentration and position in the host semiconductor lattice. Concentrations of these "controlled" impurities are as low as one part per billion, and the depths to which they are diffused, implanted, or otherwise introduced are controlled often to a fraction of a micron. Should the level of noncontrolled impurities in or on the semiconductor reach some critical value, especially before a high temperature process occurs, device failure can be expected. Often, the concentration of impurities necessary to degrade device performance is only a fraction of the "controlled" amount of impurity dopant necessary to provide device performance.

A.1.1.1 Basic Material - The beginning of life for a silicon microwave device is the preparation of bulk silicon which occurs in a quartz crucible at temperatures exceeding 1,400°C in an atmosphere of ultrapure argon. Depending on the resistivity desired, controlled amounts of dopant (usually highly purified elemental boron, arsenic, or antimony) are added to the melt, and a crystal seed of the appropriate orientation is suspended at the interface. Slowly, the crystal is "pulled" from the melt; the structure, defect content, and diameter are controlled by the rate of pull. When the desired length is obtained, the ingot is removed.

If very high resistivity (e.g., 1,000-10,000 ohm-cm) silicon were desired, a process of purification called zone refining would be performed on the ingot. During this process, a molten zone, in which the dissolved impurities are preferentially segregated, is slowly moved down the length of the ingot and crystallized at the end, where, after repeated passes, it is cut off and discarded.

Mechanical and chemical operations then follow, as the ingot is surface-ground, etched chemically to remove mechanical damage, cut into slices with a diamond saw, etched chemically to remove saw damage, and finally chemically and mechanically polished. The polished wafers are evaluated for resistivity and then put into stock to await subsequent epitaxy.

Epitaxial growth of silicon is a chemical vapor deposition process usually carried out at temperatures in excess of 900°C, onto silicon or sapphire (Al_2O_3) substrate. During this process, bulk silicon wafers, doped to a very low resistivity (0.002–0.01 ohm·cm) either with arsenic, antimony or phosphorous for n^+ type, and boron for p^+ type, are placed flat on a graphite or silicon carbide coated susceptor. The side of the wafer on which epitaxial growth is to occur has been highly polished chemically and mechanically. By means of RF induced heating, the susceptor and silicon wafer are brought to an elevated temperature, where the slices are given a surface cleaning by means of the etching reaction:



After etching the surface slightly (perhaps 0.5 mil of silicon is removed), the chemical vapor deposition is initiated. For example, silane is decomposed in the presence of hydrogen by the following:



At elevated temperatures, the silicon atoms have enough thermal energy on the surface to be able to seek out crystalline sites, where they condense, thus continuing the crystalline structure, and hence the name, epitaxial growth.

After epitaxial growth, thickness of the epitaxial layer is generally measured by an infrared reflectance technique, which is analogous to the Bragg technique of X-ray analysis for crystal structure. Thus, the thickness of the layer can be determined by the spacing of the interference fringes in the infrared reflectance spectrum. In addition to this nondestructive test, angle lapping or cross sectioning and staining can be used to observe and measure the depth of the metallurgical interface; however, this latter is a destructive technique and is only performed on a sample basis.

The resistivity of the epitaxial layer can be determined by four-point probe measurement. The profile of the layer, and abruptness or gradedness of the interface can be determined analytically by either a differential capacitance technique

or the Copeland technique, named after its inventor. In either technique, the actual profile, i.e., impurity atoms as a function of layer thickness, is obtained. These data are usually presented in graphic form so that very quickly one can conclude much about the starting material.

At this point, the silicon wafers (referred to as n/n^+ or p/p^+) are put into inventory, with their identifying characteristics (resistivity, thickness of layer, resistivity and dopant type in the substrate and epitaxial run number).

A. 1. 1. 2 Device Processing

A. 1. 1. 2. 1 General Environment

Before considering a more formal process flow chart for the manufacture of silicon microwave devices, let us consider the manner and environment wherein silicon wafers are processed. Silicon wafers are typically processed in batches to minimize wafer handling and breakage; these batches are transported in containers which have been dutifully cleaned and are handled either by tweezers or vacuum pickups which have been thoroughly degreased. Finger or glove contact is never allowed and individual handling is minimized. Storage of wafers at selected points in the process is normally at points where the silicon is protected with a silicon dioxide layer, and the wafers are in closed containers, usually in an inert gas atmosphere.

The typical fabrication process now becomes more specific for the actual final device parameters needed. Wafers are drawn from inventory in a lot and, accompanied by a lot traveler indicating the process steps and control points, are started through the process. Generally, in the mesa or planar process, wafers are subjected to high temperature thermal oxidation, chemical cleaning, high temperature boron or phosphorous diffusion, photolithography, etching, solvent cleaning, and vacuum or wet metallization. The sequence depends on whether a mesa device, or the more recent planar device, is desired.

Process fabrication facilities are typically laminar flow, Class 100 (or at least Class 100 in the process areas), with particle counts monitored on a scheduled basis. Class 100 indicates no more than 100 particles (whose maximum

size is 10^{-4} cm (1 micron) per cubic foot of air. Temperature and humidity control are necessary and must be constant from day to day.

A.1.1.2.2 Types of Devices

Microwave semiconductor devices may be constructed in either a planar or a mesa configuration. Representative examples of these two types of devices utilized for PIN diodes are shown in Figure A-1 and a typical mesa tuning varactor structure is shown in Figure A-2.

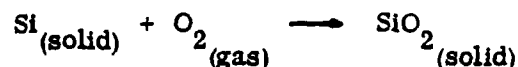
A generalized process flow chart for the planar process is shown in Table A-1 and the process subsequent to epitaxial growth and prior to encapsulation is shown schematically in Figure A-3.

A generalized process flow chart for the mesa process is shown in Table A-2 and this process is shown schematically in Figure A-4.

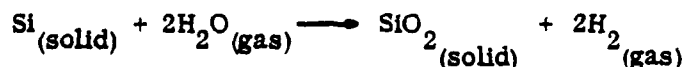
A.1.1.2.3 General Processes

The major processes involved in these devices are thermal oxidation, photolithography, boron diffusion mesa etching, contact metallization, dicing and encapsulation. Implicit in these processes are wafer cleaning procedures at each step of the processing.

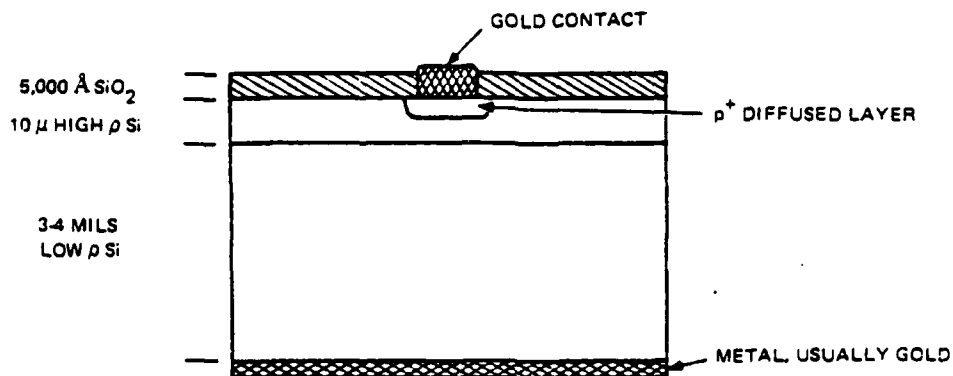
Thermal oxidation is performed on silicon for several reasons, depending on the point in the process. One function of the grown silicon dioxide layer is to mask areas of the silicon from the dopant atoms to be introduced later. Thus, in the planar process, 2,000-6,000 Å of SiO_2 is grown thermally by the following reactions:



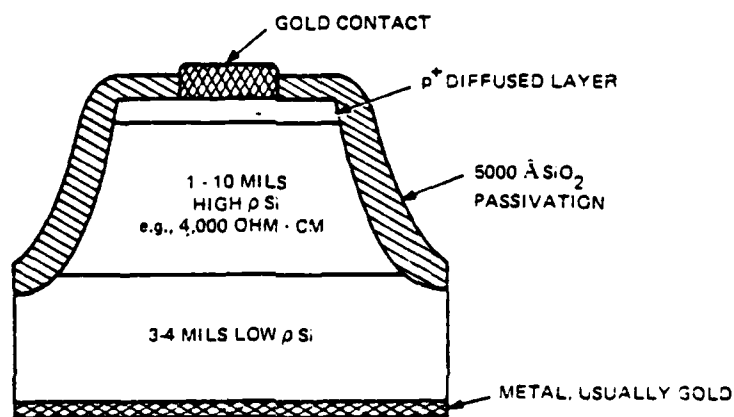
or



depending on whether the oxidation is performed in a wet or dry O_2 atmosphere. Reasonable oxidation rates for silicon occur in the temperature range of 900°C to 1,200°C. An equally or more important function of an SiO_2 layer is to passivate the



a. Planar PIN Chip



b. Mesa PIN Chip

Figure A-1. Representative Examples of Planar and Mesa Devices

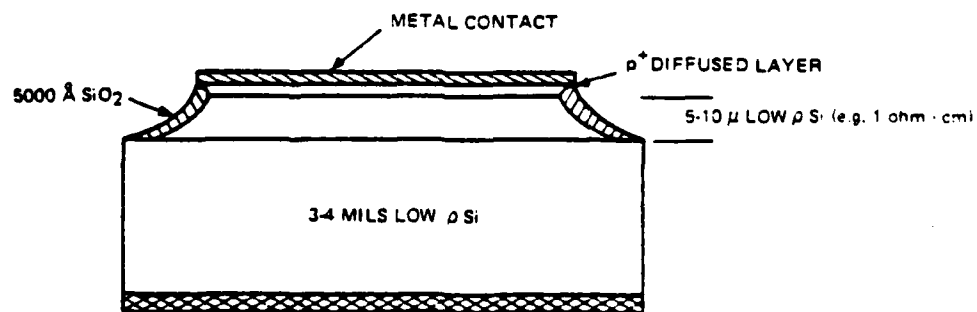


Figure A-2. Mesa Tuning Varactor Chip

52-R-76-13

TABLE A-1. GENERALIZED PROCESS FLOW CHART - PLANAR DEVICE

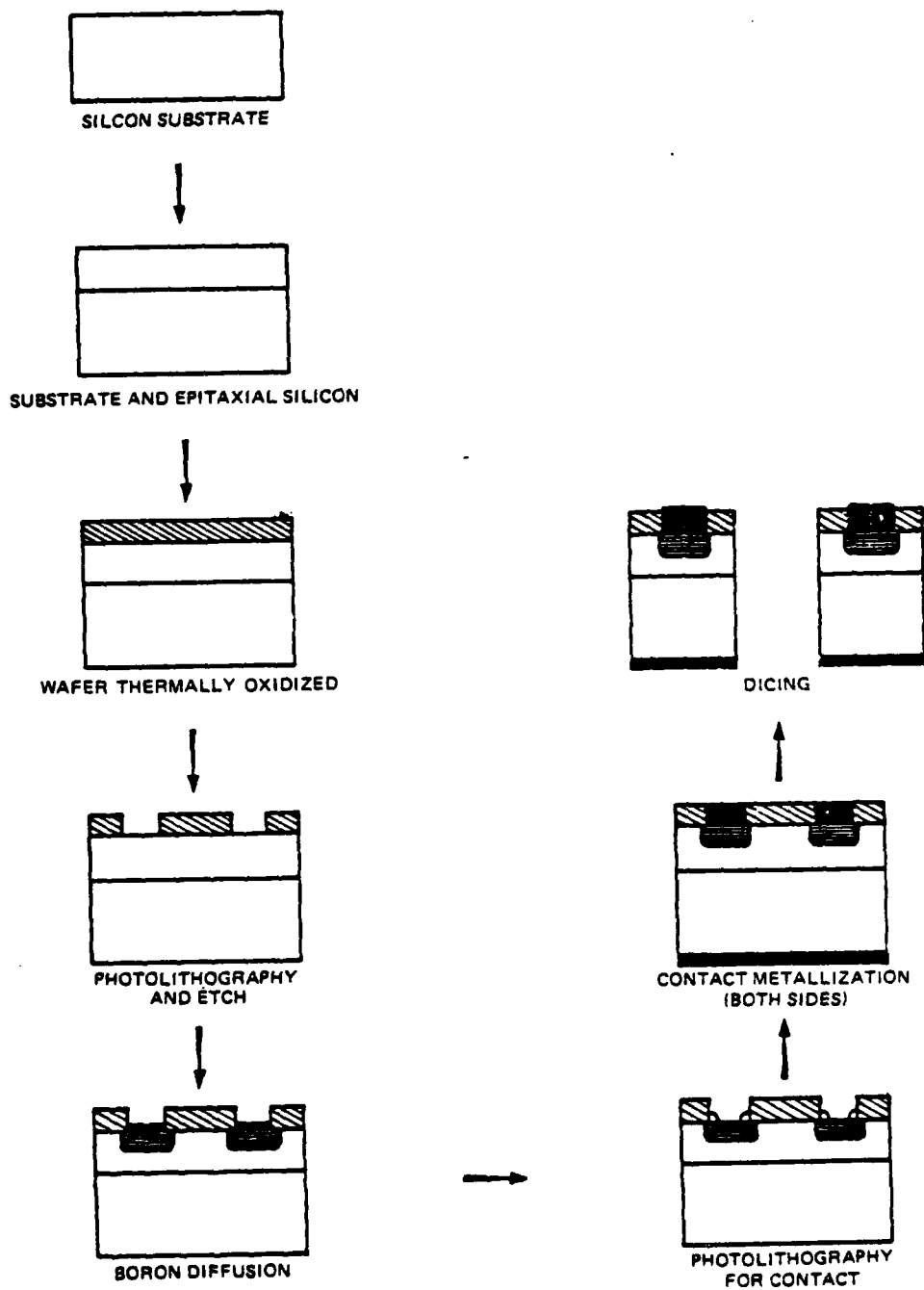
Substrate: Low resistivity antimony or arsenic doped polished silicon

- | | |
|--------------------------------|---------------------------------------|
| 1. Epitaxial Growth | 8. Thickness Adjustment |
| 2. Clean | 9. Contact Metallization - Both Sides |
| 3. Thermal Oxidation | 10. Dicing |
| 4. Photolithography | 11. Die Mount |
| 5. Boron Deposit and Diffusion | 12. Wire Bond |
| 6. Thermal Oxidation | 13. Cap (or Seal) |
| 7. Photolithography - Contact | 14. Test and Screen |
| | 15. Ship, Inventory |

TABLE A-2. GENERALIZED PROCESS FLOW CHART - MESA DEVICE

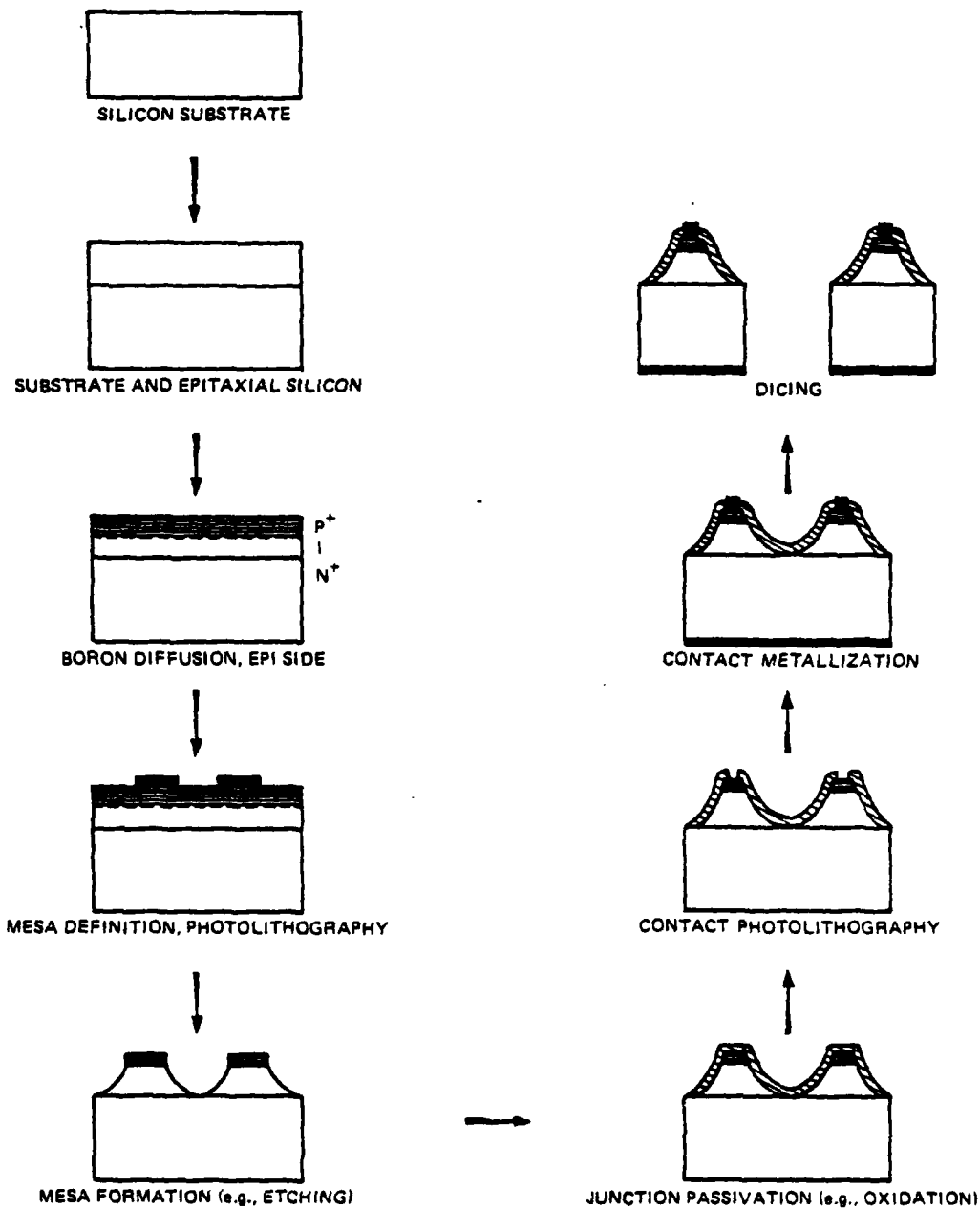
SUBSTRATES

- | | |
|------------------------------------|---------------------------------------|
| 1. Epitaxial Growth | 10. Photolithography |
| 2. Clean | 11. Thickness Adjustment |
| 3. Thermal Oxidation | 12. Contact Metallization, Both Sides |
| 4. Mount and Strip Oxide, Epi Side | 13. Dicing |
| 5. Boron Deposit and Diffusion | 14. Die Mount |
| 6. Thermal Oxidation | 15. Wire Bond |
| 7. Photolithography | 16. Capping (or Sealing) |
| 8. Mesa Etching | 17. Test and Screen |
| 9. Mesa Passivation | 18. Ship, Inventory |



92-R-76-14

Figure A-3. Typical Process Sequence, Planar Chips



52-R-76-15

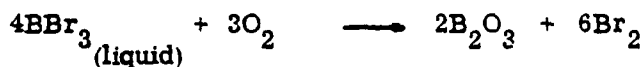
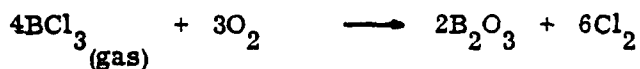
Figure A-4. Typical Process Sequence, Mesa Chips

junction. Since the electric field at the junction is on the order of 10^6 volts/cm at the breakdown voltage, it is necessary for device stability and reliability that the junction be somehow protected against invasion of foreign species, arcing, moisture, and other degrading modes. Silicon dioxide, to a great degree, provides this function.

Photoresist technology is used to allow predetermined areas in the oxide to be dissolved away, exposing the silicon. Here, a film of photosensitive organic material is applied to the wafer and the solvents are thermally driven out. Since this material is sensitive to certain wavelengths of ultraviolet radiation, exposing areas to this radiation causes rapid (virtually instantaneous) polymerization to occur. Areas which are masked from the radiation remain unpolymerized and soluble in certain solvents. Thus, a predetermined pattern from a glass plate can be transferred to the photoresist film and then, by chemical etching, into the silicon dioxide film. The usefulness of the photoresist now over, it is stripped chemically or by a plasma so as to allow the silicon wafer a thorough cleaning.

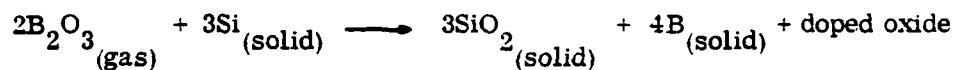
Boron and phosphorus are the standard dopants used in the microwave industry for introducing the p-n junction into silicon. The sources for these are many; the degrees of purity and types of contaminants vary depending on whether gaseous, liquid, or solid diffusion sources are used. The general mechanism in all cases, however, involves conversion of the original compound to some volatile oxide, transport of the oxide to the silicon surface, dissolution of the element within the surface, and solid state diffusion from the surface to a predetermined depth, dependent on surface concentration, time, and temperatures. Some examples of the doping reactions are given below.

For boron:

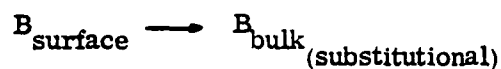




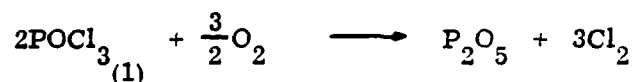
then



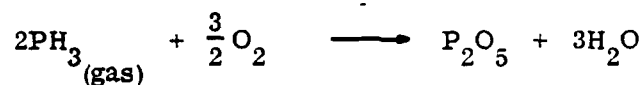
and



For phosphorus, analogous reactions occur:



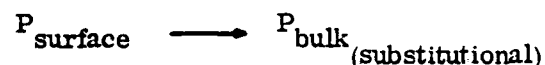
or



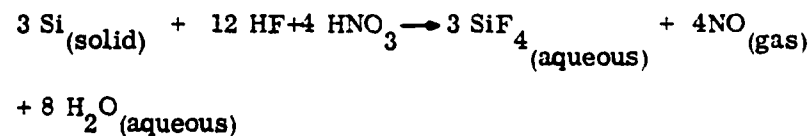
then



finally,



Mesa etching is a chemical step in which the selective dissolution of silicon is carried out. Usually, silicon etches for mesa formation are mixtures of nitric and hydrofluoric acids, wherein the mechanism of the reaction involves oxidation of the silicon and subsequent dissolution of the oxide by the hydrofluoric acid present. Occasionally acetic acid is used as a reaction moderator, affecting the degree of ionization of the nitric acid present.* The overall reaction can be considered to be:



*H. Robbins and R. Schwartz, J Elec. Soc. Vol. 107, No. 2, pp. 108-111

Areas are preselected for etching by exposing the silicon surface to the action of the etchant. Areas not to be etched are said to be masked against the etchant; masking can be affected by photoresist, thermal oxide, silicon nitride or certain waxes. The depth of the etch is usually measured by mechanical means (e.g., micrometer) and can be controlled electrically by both measurement of V_B and capacitance at some bias voltage.

Metallizations can be performed either wet or dry, by plating or by vacuum techniques. Filament evaporation, RF and DC sputtering, electron beam evaporation are all useful in metallizing wafers. Problems can occur even at this stage of processing due to foreign chemicals in the plating baths, co-deposition in the evaporation or sputtering, and radiation damage in RF sputtering to name a few. From a control point of view, contact resistance and adhesion are the prime considerations of a metallization scheme. Reliability (mean-time-before-failure) with respect to metallization dictates the type of metal(s) used, and contact resistance and adhesion dictates the method of applying these to the silicon.

Dicing silicon wafers can be done in several ways, among them sawing, scribing, laser cutting, and etching. Since, at this stage, no further high temperature processing will occur, there is concern now only for the surface condition of the silicon. Voltage breakdown and capacitance are affected by surface contamination on the chip. Lifetime and reliability can be affected by microcracks or saw damage propagating into the active area of the chip. Bonding can be prevented by even a monolayer of impurities on the contact metallization surface. A good indicator of surface condition and one which is used frequently to test diodes, is a high temperature reverse bias condition, for a prolonged period of time, monitoring leakage current. Contamination on the chip will be observed as an increasing leakage current with time, and premature device failure. Well-passivated, clean, non-contaminated chips often have leakage currents of less than a nanoampere before and after reverse bias at elevated temperature.

It is at this stage in the process when chips are assembled into diodes. Die mounting, wire bonding, or strapping and encapsulation, either by sealing or capping, are relatively lower temperature operations than the chip has seen earlier and, usually, surface contamination would be the prime reason for failure.

A. 1. 1. 2. 4 Chemicals Used

During these process steps, the more highly controlled silicon slices encounter any or all of the less controlled chemicals listed in Table A-3. Combining with these chemicals are the high temperature operations necessary to provide reasonable times for the solid state dissolution and diffusion of controlled amounts of impurities. It now becomes evident that any of these chemical or thermal interactions with the silicon wafers provides possible ingress to an unwanted species, leading to premature device failure.

Chemicals used in the fabrication of silicon microwave devices encompass the three physical states of materials: solids, liquids, and gases. Solid chemicals are normally zone refined and analyzed for impurities. Liquid chemicals are specified as electronic or MOS grade by most suppliers. These are normally analyzed wet chemical techniques complemented by atomic absorption or emission techniques. The analyses for the particular lot are not reported but are guaranteed to be within specified maximum values. The analyses are generally inorganic, covering metal species, nitrates and sulfates, as well as chlorides.

The specification of impurity levels by maximum permissible levels rather than actual measured levels opens the possibility that, from lot to lot, actual amounts of metallic impurity may, and probably do, vary within the manufacturer's specification. One particular lot might contain two parts per billion of sodium, while the next might contain 200 parts per billion; both lots, however, meeting the supplier specification of 15 parts per million maximum. The variation in the actual amount of contaminant from lot to lot could be sufficient to cause wild fluctuations in the silicon process yields from run to run. In addition, since the highly purified chemicals are routinely used in batch amounts, either in pure form, mixed with other acids, or diluted with deionized water, other avenues of contamination are possible. The

cleanliness of the reaction vessels, which are usually cleaned in similar chemicals and rinsed in the same deionized water, is essential.

TABLE A-3. LESS CONTROLLED CHEMICALS

<u>Acids</u>	<u>Solvents</u>	<u>Aqueous</u>
Hydrofluoric	Methanol	DI Water
Hydrochloric	2-Propanol	Plating Solutions
Acetic	Xylene	Metal Etches
Nitric	Benzene	
Sulfuric	Trichloroethylene	
	Methylene Chloride	
	Methyl Ethyl Ketone	
	Acetone	
<u>Gases</u>	<u>Liquids</u>	<u>Solids</u>
Hydrogen	Phosphorus Oxychloride	Waxes
Argon	Boron Tribromide	Abrasives
Nitrogen		Boron and Phosphorus Compounds
Oxygen		
Silane		
Diborane		
Phosphine		
Hydrogen Chloride		

Water is necessary at most points in the process for cleansing or rinsing operations and has to be extensively purified before usage. Raw city water, either from wells or reservoirs, is typically filtered, upgraded by any of several methods including reverse osmosis and dialysis, and finally polished to the theoretical limit of purity for the measured temperature usually reaching 18 megohms at 25°C. The final stage of purification is normally an ion exchange technique, followed by sub-micron filtering and ultraviolet sterilization. Final polishing stations may be located at the outlet locations to insure no degradation of the water in the delivery

lines. In addition, frequently monitoring the counts of bacteria present in the more stagnant drops insures that a high quality water will be delivered to all stations. Chemical sterilization can be used in the system when or if bacteria counts rise to an unacceptable level. Thus, the process water is considered to be as clean and impurity-free as is possible for liquid phase systems. To say this quantitatively, however, has not been possible until only recently with the advent of sub-trace quantitative and qualitative analytical tools.

Finally, the gases used in device fabrication are generally ultrapure. Where possible, liquid sources are used, in close proximity to the process laboratory. Gas delivery is via stainless steel tubing which has been thoroughly pressurized and leak checked.

A. 1. 1. 2. 5 Critical Areas of Processing and Control Points

Those areas of the wafer processing which are the most critical are those which involve processing at elevated temperatures. These areas, the formation of the thermal oxide and the formation of the p-n junction, are critical to the proper operation of the device. Even more importantly, the areas provide the conditions under which any contamination of the surface of the wafer or the mesas, from cleaning or etching procedures or contaminated ambient conditions, can be incorporated into the finished device.

The properties of the thermal oxide are evaluated both physically and electrically. The physical characterization involves the measurements of thickness and pinhole density.

For oxide thickness measurement, a test monitor accompanies the lot being processed; this monitor is measured by either a fringe count, or by ellipsometry, to determine the thickness. Pinhole density (or film integrity) can be measured by immersing the wafer in a suitable electrolytic cell as the cathode, and observing (and counting) the sites where H_2 evolution occurs by cathodic reduction. Normally, the anode is a noble metal, although copper could be used, for permanently "decorating" the pinhole site with copper, attracted to the cathodic site and reduced only at that site.

Electrically, the quality of the oxide film can be determined by borrowing from the MOS technology the determination of the shift in the flat band voltage caused by mobile and immobile charged species and interfacial states trapped in the oxide film. Sodium ion, incomplete silicon-oxide bonds, hydrogen ion and other impurities result in charges in the oxide, in the order of $1 \times 10^{10} - 1 \times 10^{12}$ charges/cm². Some of these charges are mobile with temperature and electric field, and cause inversion layers in silicon. These inversions lead to reduction in breakdown voltage, instability in leakage current, and tuning problems such as post tuning drift. Furnaces are monitored for variations in flat band voltage shifts and bias stressing at elevated temperatures, and when shifts occur beyond some acceptable value, the quartzware is either cleaned or replaced. HCl gas has been found to reduce Q_{ss} levels (lesser flat band shifts) in silicon dioxide films when incorporated in the film, as well as provide adequate cleaning of furnace tubes by reacting with sodium and other species migrating through the quartzware and carrying them off in the vapor phase.

Controls in the formation of the p-n junction are also used at this point in the process. The delivery ability of the doping system is monitored within each run by measuring the sheet resistance of the silicon by way of a four-point probe measurement, either on a test monitor or on a test pattern on the actual patterned wafer. The sheet resistance is directly related to the concentration of dopant in the surface of the wafer, and the depth to which it is diffused. In addition, the actual depth can be measured (in a test monitor) by angle lapping and staining the junction. Fringe counts (e. g., thallium light) can be used to arrive at the actual junction depth. The integrity of the junction, as well as the type of junction, can be measured electrically at this process point. Voltage breakdown and capacitance voltage relationships can be determined. The "abruptness" or degree of "gradedness" of the junction can be readily determined from the CV relationship. The quality of high resistivity I-region in a PIN slice after processing can be observed in the "reach through" (or punch through) voltage. The lower the punch through voltage, the higher the resistivity, for a given thickness of I-region. Finally, the gradedness of the interface between the high and low resistivity silicon can be seen from the CV characteristic, appearing as a more negatively sloped plot for the graded interface, and a flatter plot for the

more abrupt interface. Minority carrier lifetime to a first approximation can also be measured at this point, provided one can obtain good contact between the probe and the wafer. This measurement is normally a pulse measurement between forward and reverse bias and is observed on a sampling oscilloscope. The measurement can provide information on the later performance of the diode from an R_g point of view, as well as indicate problems in the process, either thermal or chemical.

One example might be cited: prior to a high temperature thermal oxidation, a silicon wafer, designed to provide microwave limiter chips (e.g., for a TR duplexer) is subjected to a stringent cleaning operation. Unknown to the operator, metallic contamination, gold, is present in one of the acid solutions used for cleaning. The concentration need only be a few parts per billion. The mechanism of ingress can then be pictured:

- a. Diffusion of gold contaminant to silicon surface.
 - b. Physical or chemical absorption onto surface, in a concentration satisfying the equilibrium distribution with the solution.
 - c. Solid state diffusion of the contaminant, either substitutionally or interstitially, into the silicon lattice during the high temperature processing stage.
- During this step, the concentration of contaminant in the bulk will be determined by the surface concentration, time and temperature, and the solid solubility of the contaminant at the given temperature.

These contaminant atoms are now frozen in the crystalline lattice, where their effect will be to provide trapping centers for minority carriers, drastically decreasing minority carrier lifetime. This phenomenon has a marked influence on the series resistance of the chip which will be observed as increased insertion loss for the diode and usually signifies the loss of the wafer. However, because insertion loss is not meaningful at this point in the process, the wafer would continue through the dicing operation, then progress to die mounting, wire bonding and capping. All the while, manufacturing costs are being accumulated for this particular wafer, for which no return will be observed. The indicator, of course, during wafer processing,

is the measurement of lifetime. But even where the wafer is discarded at that point, the question would trouble many a process engineer: why the low lifetime for this material? Is it contamination, and if so, what, and from where? Has anything else become contaminated because of it?

A. 1.2 Microwave Device Theory and Design

This section will present a generalized approach to microwave device theory and design concentrating on two types of devices only: PIN diode and tuning varactor. The approach will emphasize general principles of design and associated performance, design parameters, optimized and practical designs, the effect of extraneous conditions (such as material defects, process deficiencies, wrong assembly techniques, etc.) on the device performance.

A. 1.2.1 PIN Diode - A PIN diode is a semiconductor device which controls power in a microwave circuit. Power control is achieved in the form of switching and/or attenuation; and it is accomplished by presenting to the circuit an "open" circuit - "short" circuit combination and/or variable insertion loss behavior, respectively. The PIN diode is ideally suited for such power control functions as under reverse bias it will be a low-loss reactance (with very small capacitance) and under forward bias a very small resistor.

The design theory presentation in this subsection will be made in a form which relates the physics of the device to the performance parameters vis a vis environmental properties influenced during processing. The approach will be general inasmuch as understanding of these relationships is concerned; that is, specialization will occur only when it helps in understanding the properties of the device.

The theory will describe the free-carrier behavior as this is the stepping stone to the full realization of device parameters. The things that influence and are associated with these parameters will, therefore, also be elucidated.

A. 1.2.1.1 Minority Carrier Model

If the intrinsic region is assumed to be truly "intrinsic," then the analysis of the minority carriers become meaningful under forward bias. This is

because only under forward bias is there any appreciable amount of minority carrier present in the I-region.

We start with the current-continuity equation for holes:

$$\frac{\partial p}{\partial t} = -\frac{p}{\tau_p} - \frac{1}{e} \nabla J_p \quad (1)$$

where p is the hole concentration and J_p is the hole current density. Noting that

$$J_p = -e D_p \nabla p \quad (2)$$

we derive for the steady state ($\frac{\partial p}{\partial t} = 0$) and one-dimensional cases:

$$\frac{d^2 p}{dx^2} - \frac{p}{\tau_p D_p} = 0 \quad (3)$$

The same formulation for the electron concentration, n , results in:

$$\frac{d^2 n}{dx^2} - \frac{n}{\tau_n D_n} = 0 \quad (4)$$

One point of paramount importance must be noted here. The I-region must obey the charge neutrality law at every point. Therefore

$$n(x) = p(x) \quad (5)$$

This condition will impose severe rules on electrons and holes as far as the recombination mechanism is concerned. We shall see this more clearly, later.

The solutions to Equations (3) and (4) are of the form

$$p = Ae^{\frac{x}{L_p}} + Be^{-\frac{x}{L_p}} \quad (6)$$

$$n = Ce^{\frac{x}{L_n}} + De^{-\frac{x}{L_n}} \quad (7)$$

where

$$L_p = \sqrt{\tau_p D_p} \quad \text{and} \quad L_n = \sqrt{\tau_n D_n}$$

A, B, C and D are constants to be determined by the boundary conditions. The prime boundary condition is, of course, Equation (5) which dictates that

$$L_p = L_n = L$$

and

$$A = C$$

$$B = D$$

The other boundary condition is that

$$p(0) = n_i e^{\frac{qV_F}{kT}} = n(W_I)$$

at sufficiently high forward bias. With these boundary conditions the solution becomes

$$p(x) = n(x) = n_i e^{\frac{qV_F}{kT}} \left\{ \frac{1 - e^{-\frac{W_I}{L}}}{2 \sinh\left(\frac{W_I}{L}\right)} e^{\frac{x}{L}} + \frac{e^{\frac{W_I}{L}} - 1}{2 \sinh\left(\frac{W_I}{L}\right)} e^{-\frac{x}{L}} \right\} \quad (8)$$

The graphical representation of this equation is shown in Figure A-5. Equation (8) will be valid even when the i-region is not quite "intrinsic." In fact, the mathematical difference for the forward bias case between 100 and 10,000 ohm · cm is negligible. Equation (8) is also valid for any W_I/L ratio.

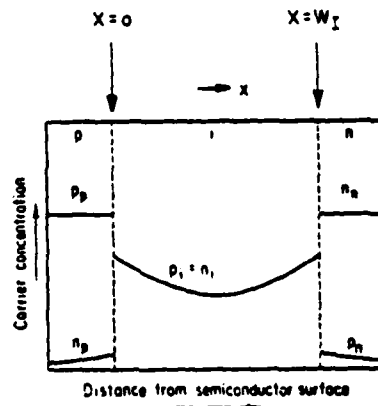


Figure A-5. Typical Carrier Distribution in i Layer of p-i-n Diode under Forward Bias. The p Layer, i Layer, and n Layer Are Assumed To Be Uniformly Doped, with Abrupt Transitions in Doping between Layers. Carrier Densities p_i and n_i Are Densities in the Presence of Injection, rather than Intrinsic Carrier Densities.

A. 1. 2. 1. 2 Calculations of Diode Impedance

The imposed conditions on recombination mechanism, as we have seen above, dictated that

$$T_p = T_n = T \quad (9)$$

This enables us to safely assume an ambipolar mobility μ_{Ap} which is

$$\mu_{Ap} = \frac{2\mu_p\mu_n}{\mu_p + \mu_n} \quad (10)$$

Conceptually this μ_{Ap} which is about $610 \text{ cm}^2/\text{VS}$ in silicon is the effective average of the hole and electron mobilities.

With these assumptions we can now calculate the forward bias resistance, R_I . Note that

$$R_I = \frac{W_I}{\sigma A} = \frac{W_I}{Aq(\mu_p p + \mu_n n)} = \frac{W_I}{2qA\mu_{Ap}p} \quad (11)$$

But the injected charge Q_p , is directly proportional to the forward bias current.

$$Q_p = qpAW_I = I_F\tau \quad (12)$$

Combining Equations (5), (12) and (11) yields

$$R_I = \frac{W_I^2}{2\mu_{Ap}I_F\tau} \quad (13)$$

As can be seen, R_I is independent of diode area, A , but inversely proportional to lifetime and bias current. Since this equation is very widely used, a few words of caution are in order:

(a) We don't necessarily keep R_I constant by changing A because, generally speaking, I_F decreases with a decrease in A . This is due to I -region carriers now being nearer to the periphery where recombination can occur more rapidly.

(b) R_I decreases with I_F so long as τ remains constant. It should be recognized that as I_F increases, carrier density increases, and the recombination

probability increases, decreasing τ . Furthermore, saturation is reached when p and n increase sufficiently so that substantial injection (holes into the n^+ region and electrons into the p^+ region) becomes significant, further increasing recombination probability. Put simply, if there are high densities of electrons and holes in the I-region, their chance for recombining increases, decreasing the average lifetime.

During reverse bias the impedance will not only have a resistive component (as in the forward bias case) but also a reactive component which will actually dominate the diode behavior after punch-through. The study of the reverse bias necessitates the use of finite resistivity for reasons of realism. Now, we start with Poisson's Law

$$\frac{dE}{dx} = \frac{q}{\epsilon} N_a \quad (14)$$

Integrating Equation (14) and applying the boundary condition that the electronic field, E , vanishes at W

$$E = \frac{q}{\epsilon} N_a (W-x) \quad (15)$$

A second integration over the same depletion region gives the junction voltage,

$V_j = -V_a + V_d$ (where $-V_a$ is the applied reverse bias and V_d is the built-in voltage).

$$V_j = -V_a + V_d = \frac{q}{\epsilon} N_a \frac{W^2}{2} \quad (16)$$

This gives us the standard formula relating depletion width, W , to applied potential.

We can now calculate the values of C_j , C_i , X_j , X_i , R_j and R_i . These elements are depicted in Figure A-6. Since R_j is very large compared to X_i it is quite safe to approximate the total impedance of the I-region by

$$Z = R + jX \approx j \left(X_j + \frac{X_i R_i}{R_i + jX_i} \right) \quad (17)$$

Expressions for C_j , C_i and R_i are

$$C_j = \frac{\epsilon A}{W}; \quad C_i = \frac{\epsilon A}{W_i - W}; \quad R_i = \frac{\rho}{A} W_i - W \quad (18)$$

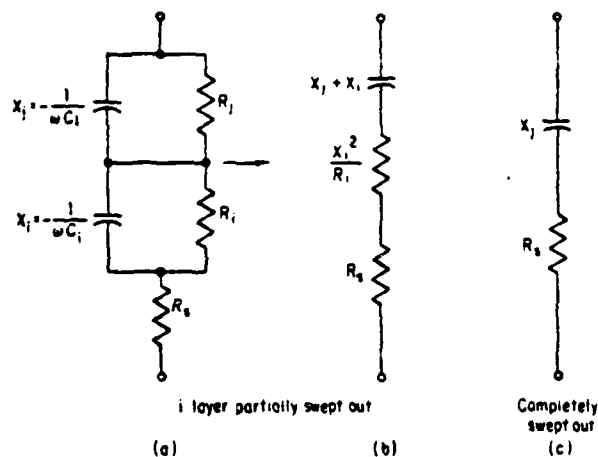


Figure A-6. Approximate Equivalent Networks for p-i-n Diodes under Reverse Bias at Microwave Frequencies

Substituting (18) into (17) gives us the series resistance and reactance of the I-region

$$R_s = \frac{\rho(W_I - W)}{A(\rho^2 W^2 \epsilon^2 + 1)} \quad \text{and} \quad X = \frac{-\rho^2 W \epsilon}{A(\rho^2 W^2 \epsilon^2 + 1)} \left(W_I + \frac{W}{\rho^2 W^2 \epsilon} \right) \quad (19)$$

If $\rho W \epsilon \gg 1$ (as is the case for a good microwave PIN device), we can approximate the resistance and reactance as

$$R \approx \frac{W_I - \left[\frac{2 \epsilon \mu \rho (-V_a + V_d)}{W^2 2A} \right]^{1/2}}{W^2 2A} \quad \text{for } 0 \geq V_a \geq V_d - \frac{W_I^2}{2 \epsilon \mu \rho}$$

$$R = 0 \quad \text{for } V_a < V_d - \frac{W_I^2}{2 \epsilon \mu \rho}$$

$$X \approx \frac{-W_I}{W \epsilon A} \quad (20)$$

The above analysis has shown that if the operating frequency and the I-region resistivity are high, the capacitance of the I-layer is independent of the bias voltage and is equal to that of a parallel-plate capacitor of separation W_I and plate area A . It has also been shown that the resistance of the I-region decreases with increasing bias voltage, V_a , as well as with increasing operating frequency, I-layer resistivity and permittivity. Furthermore, it is obvious from Equation (20) that reverse bias

impedance measurements, no matter how accurately they may be performed, are insensitive to lifetime effects. Therefore, for example, changing conditions in the process will not exhibit themselves in the reverse bias impedance parameters.

A.1.2.1.3 Switching Speed

So far we have seen, quantitatively, how minority carriers are distributed inside the I-layer and how they determine the forward resistance of the diode. We have also observed, again quantitatively, the reverse bias behavior of the diode. Certainly, minority carrier recombination mechanisms play a first order role only in the forward bias case.

If one is to study surface effects it is important to identify as many mechanisms as possible which are influenced by surface recombination so that independent inputs are provided for analysis of the surface conditions. Even though switching speed, at first glance, appears as one such possibility, a closer look states otherwise. A properly designed driver circuit can artificially "suck-out" the stored charge. Hence, switching speed can be made to vary over a range even with the same lifetime inside the P-N diode. A better measure of the switching speed is really the transit time of the carriers through the I-region by the diffusion process.

The average transit time, t_w is given by

$$t_w = 0.038 W^2 \quad (21)$$

Hence, the transit time is only dependent on I-region thickness and not lifetime.

It is, therefore, necessary to look for some other parameter to provide us with information on changing surface conditions. Note that

$$\frac{1}{\tau} = \frac{1}{\tau_s} + \frac{1}{\tau_b}$$

where τ_s is the surface recombination life-time and τ_b is that of the bulk. Recognizing that the reverse saturation current density, J_s is dependent on τ :

$$\begin{aligned} J_s &\sim \frac{D_n}{L_n} + \frac{D_p}{L_p} \\ &\sim \frac{1}{\sqrt{\tau_n}} + \frac{1}{\sqrt{\tau_p}} \end{aligned} \quad (22)$$

Thus, the possibility of looking at reverse leakage current, particularly close to avalanche, to identify deviations from the ideal conditions on the surface appears quite real, as we will elaborate on in subsections A.1.5 and A.1.7. We propose to observe this J_s over a long time span at high temperature to deduce meaningful information on the surface degradation.

A.1.2.2 Tuning Varactor - A tuning varactor is a device which, in most applications, changes the output frequency of an oscillator with applied dc bias. Its major function, therefore, is to present a certain variation of capacitance with voltage to a tank-circuit. What is required of a tuning varactor, in microwave applications, is, of course, much more complex. In the first place, every time the applied voltage varies a certain way, the capacitance should vary the same way. In other words, no hysteresis effect is allowed as this would engender different resonant frequencies for the same bias. Secondly, the capacitance of the diode at a given bias should be invariant in time. Namely, the resonant frequency is not allowed to drift (even 0.1% in some cases). More comment on this drift problem will be presented in subsection A.1.5. Additionally, the diode should absorb an incident power minimally and the amount of the absorbed power should not change with time. This means that the quality factor, Q , of the diode should be high (for low insertion loss) and should remain constant, as a variable load would otherwise produce instability in the circuit. In summary, it is totally insufficient to manufacture a semiconductor device performing to specifications indicated by the semiconductor theory because the device is not just a semiconductor chip but an integral part of a microwave system. Accordingly, we will present the most appropriate theory and design applicable to microwave tuning varactors but with an eye to the eventual application of the device in the system.

A.1.2.2.1 General Principles

The most general approach to tuning varactor design is to assume an abrupt junction case but with a doping profile $N(x)$ in the epitaxial layer varying exponentially:

$$N(x) = N_0 e^{kx} \text{ cm}^{-3}$$

where N_0 is the doping concentration at the surface ($X = 0$) in atoms/cm³ and k is the doping gradient factor in cm⁻¹ (or μ^{-1}). The reason for such generalization is as follows:

a. To maximize Q , the epitaxial layer thicknesses used in microwave tuning varactors are in the range of 3-10 micrometers. Hence, the diffusions in these epi layers are necessarily quite shallow (<2 microns). This invariably results in an abrupt junction the depletion into which is four to five orders of magnitude less than that into the epi layer. Therefore, no measurable error will be incurred by assuming that all the depletion is into the epi layer.

b. The doping profile in the epi layer is not as constant as it is usually assumed. This problem, which emanates mostly from the out-diffusion of dopants from the substrate and/or poor injected dopant control during the epitaxy deposition process, has the effect of changing the capacitance-voltage dependence and therefore plays a first order role in the device performance. Also, it is important to distinguish, for diagnostic reasons, the influence of a doping profile's non-constancy from the influence of ionic surface contamination on the device performance. Besides, a constant doping profile case can easily be analyzed by merely making $k = 0$. Thus, the added complexity (which is only algebraic) is compensated by useful generality.

We start our analysis by noting that:

$$\frac{d}{dx} (xy) = x \frac{dy}{dx} + y \quad (1)$$

If y is taken to be the electric field, E , then we can pursue this line of thinking by further noting that

$$\frac{d}{dx} \left(x \frac{dv}{dx} \right) = x \frac{d^2v}{dx^2} + E \quad (2)$$

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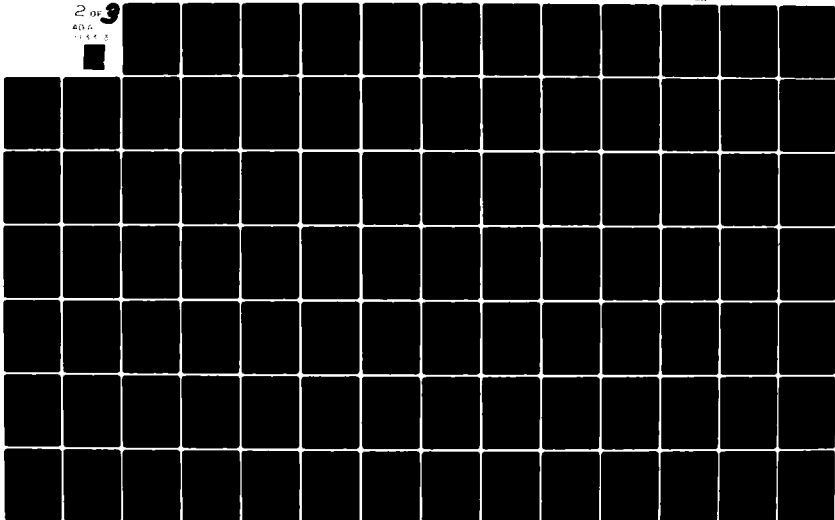
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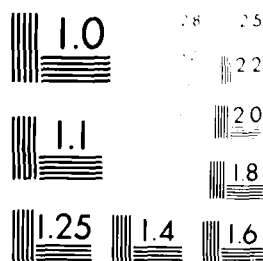
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Recognizing that the field, E , ($\frac{dv}{dx}$) is approximately zero just beyond the boundaries of the depleted region and integrating both sides of Equation (2) over the length of the depletion region, one finds that

$$\int_0^W \frac{d}{dx} \left(x \frac{dv}{dx} \right) dx = x \frac{dv}{dx} \Big|_0^W \approx 0 = \int_0^W x \frac{d^2v}{dx^2} dx + \int_0^W E dx$$

Thus
$$\int_0^W E dx = V_j = V_a + V_d = - \int_0^W x \frac{d^2v}{dx^2} dx \quad (3)$$

We know, from Poisson's Equation that

$$\frac{d^2v}{dx^2} = - \frac{q}{\epsilon_r \epsilon_0} N(x) \quad (4)$$

Substituting

$$V_j = \frac{q}{\epsilon_r \epsilon_0} \int_0^W x N(x) dx \quad (5)$$

where

$$q = 1.6 \times 10^{-19} \text{ coulombs}$$

$$\epsilon_r \epsilon_0 = 0.96 \times 10^{-12} \text{ f/cm for silicon}$$

$$N(x) = N_d(x) - N_a(x)$$

$$N_d(x) = \text{Number of donors per unit volume}$$

$$N_a(x) = \text{Number of acceptors per unit volume}$$

$$V_j = \text{Total junction voltage}$$

$$V_a = \text{Applied voltage}$$

$$V_d = \text{Diffusion potential} = \frac{kT}{q} \ln \left(\frac{N(W_1)N(W_2)}{n_1^2} \right)$$

$$W_1 = \text{Width of depletion into the n region}$$

$$W_2 = \text{Width of depletion into the p region}$$

$$W = \text{Depletion width at } V_j$$

Employing the generalized exponential relationship for the doping profile we finally obtain:

$$V_j = 1.67 \times 10^{-7} N_0 \int_0^W x e^{kx} dx \quad (6)$$

Equation (6) is the fundamental equation governing the tuning varactor.

The solution of Equation (6) is transcendental and it is given by:

$$V_j = \frac{1.67 \times 10^{-7} N_0}{k^2} \left[e^{kW} (kW - 1) + 1 \right] \quad (7)$$

A. 1. 2. 2. 2 Design Parameters

Analysis of Equation (7) yields us all the necessary interrelationships between capacitance, voltage and doping profile. Namely,

$$V_j = f(C, N_0, k)$$

where C is the capacitance per unit area.

$$C = \frac{\epsilon_r \epsilon_0}{W} \quad (8)$$

Thus

$$V_j = \frac{1.67 \times 10^{-7} N_0}{k} \left[e^{\frac{k \epsilon_r \epsilon_0}{C}} \left(\frac{k \epsilon_r \epsilon_0}{C} - 1 \right) + 1 \right] \quad (9)$$

which is our $f(C, N_0, k)$.

Equation (9) is plotted in Figure A-7 for various values of k and for $N = 10^{15} \text{ atoms} \cdot \text{cm}^{-3}$. Some representative values of k corresponding to slopes in doping profiles are presented in Table A-4.

Two important points should be noted:

a. The deviation from the square-root-law (represented by $k = 0$ line) is significant even for $k = 0.091 \mu^{-1}$. At $V_j = 30\text{V}$, for example, capacitance has increased by 20%. Capacitance ratio, therefore, between C at 4V and C at 30V has decreased by 20%. Moreover, the percent increase in capacitance gets worse at higher voltages.

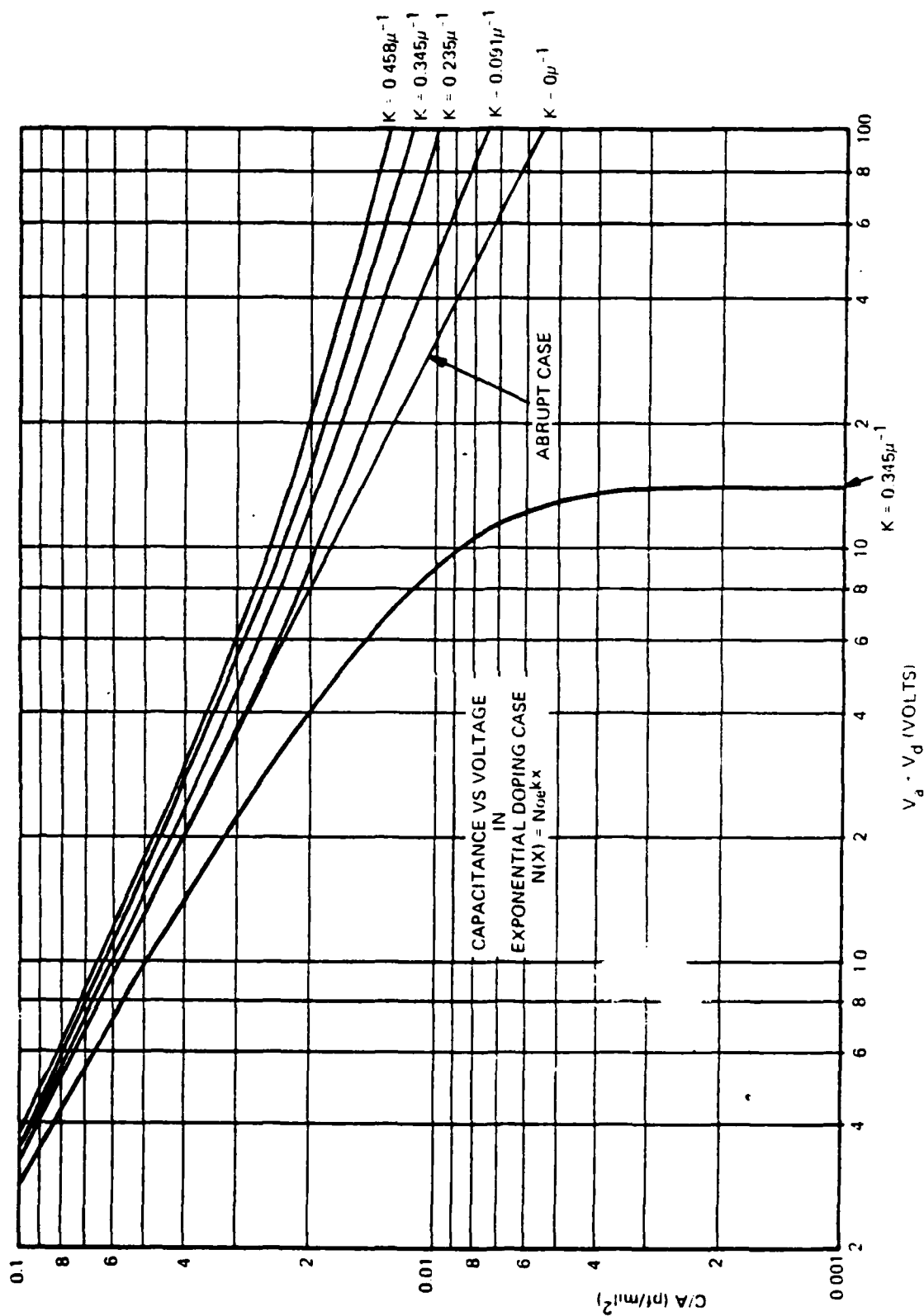


Figure A-7. Capacitance vs Voltage in Exponential Doping Case

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b. Family of curves of C vs V are all parallel for different values of N_0 (since $V_j \propto N_0$). This fact enables us to draw a C vs V curve for any desired N_0 . For example, to generate capacitance - voltage characteristics corresponding to, say $k = 0.091 \mu^{-1}$ and $N_0 = 10^{14} \text{ cm}^{-3}$, one takes the corresponding curve from Table A-4 for $N_0 = 10^{15} \text{ cm}^{-3}$ and displaces it to the left by a factor of 10. In other words, the same capacitance per unit area will be achieved at one-tenth the voltage.

TABLE A-4.

k	Doping Slope
0	0
$0.091 \mu^{-1}$	20% per 2μ
$0.168 \mu^{-1}$	40% per 2μ
$0.235 \mu^{-1}$	60% per 2μ
$0.347 \mu^{-1}$	100% per 2μ
$0.549 \mu^{-1}$	200% per 2μ

The usefulness of Table A-4 is limited in that a particular material run may result in a k -value different from that shown. It would be pure guesswork to deduce the new C - V curve on the basis of Table A-4's data alone. Accordingly, a general-purpose plot is presented in Figure A-7 whereby k -values are plotted as a function of capacitance per unit area with voltage as a parameter. To use Figure A-7, one first determines k -value from the Copeland Profilometer (Figure A-8) plot as follows:

$$k = \frac{1}{2} \ln \frac{N(2\mu)}{N_0} \mu^{-1}$$

Then a horizontal line at this k -value is drawn on the graph. Points of intersection of this line with the family of curves give the necessary (C, V) points to generate the capacitance-voltage characteristics. This C - V plot, then, is translated to the left

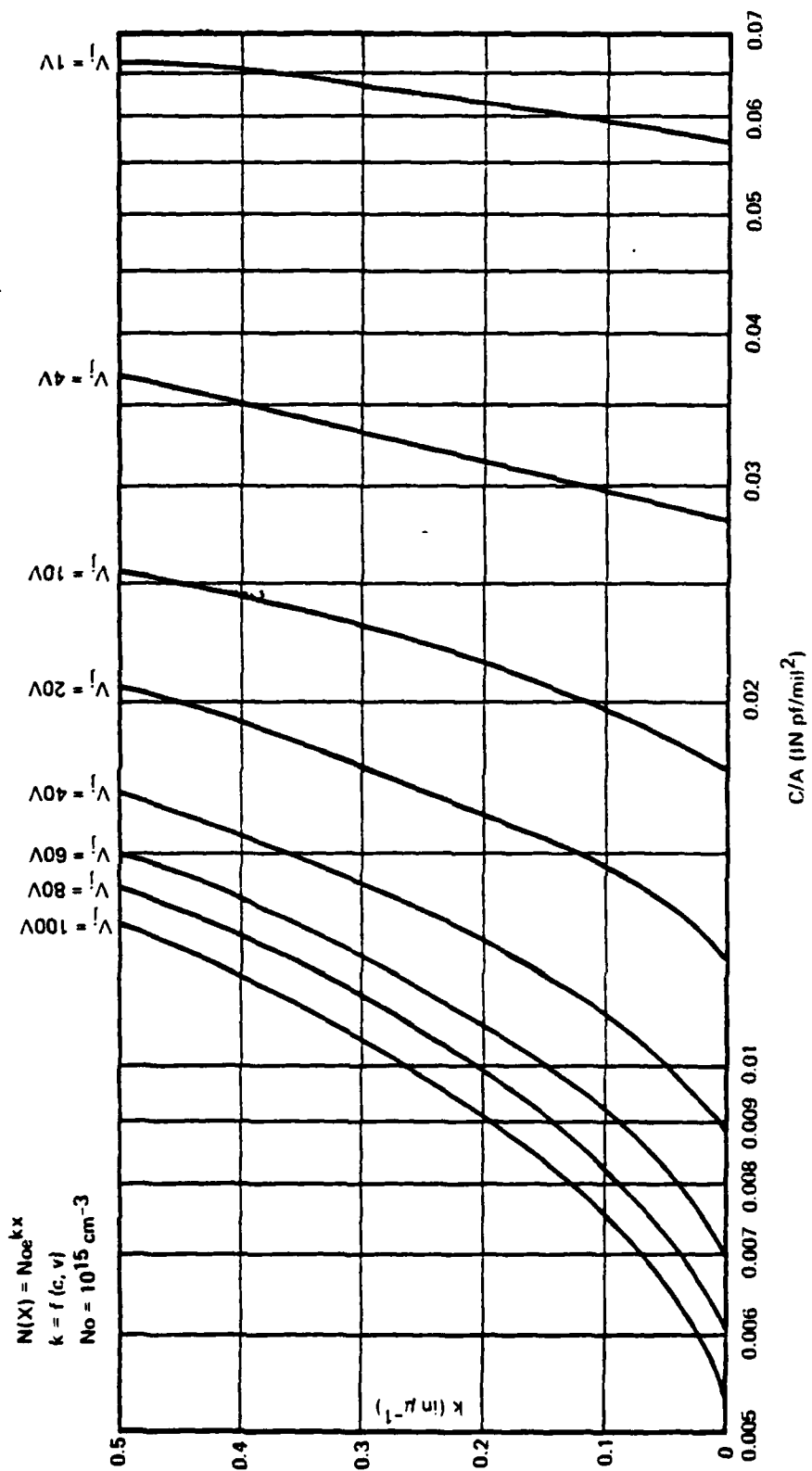


Figure A-8. Copeland Profilometer

(or right) by a factor of $N_0/10^{15}$. If $N_0 = 5 \times 10^{15}$, then the C-V plot is translated to the right by a factor of 5. If $N_0 = 5 \times 10^{14}$, then the translation is to the left by a factor of 2.

At this point we should reflect somewhat more on the meaning of Equation (7). It should be noted that

$$\lim_{k \rightarrow 0} V_j = 0.84 \times 10^{-7} N_0 W^2 \sim \frac{1}{C^2} \quad (11)$$

Therefore

$$C \rightarrow V_j^{1/2} \text{ as } k \rightarrow 0 \quad (12)$$

Hence, this generalized approach simply reduces to the case presented by the standard p-n junction theory when the doping profile becomes constant with distance.

A design theory for tuning varactors cannot be considered complete until epi thickness, W_{epi} , and quality factor, Q , are determined. For this, we will assume $k = 0$ (uniform epi case) and use applied bias, V , rather than F as only F is measurable.

$$\text{Junction Capacitance, } C_j \sim (V_a + V_d)^{-1/2} \quad (13)$$

Where $V_d \approx 0.6$ is assumed.

Now to solve for W_{epi} we go back to Equation (6) and rewrite with $k = 0$

$$V_j = 0.6 + V_a = 1.67 \times 10^{-7} N_0 \frac{W_{\text{epi}}^2}{2} \quad (14)$$

Therefore

$$W_{\text{epi}} = 3.4 \times 10^3 \left(\frac{0.6 + V_a}{N_0} \right)^{1/2} \text{ cm} \quad (15)$$

Next, we determine Q at $-4V$ (since this bias value is employed on a standard basis throughout the industry).

$$\frac{1}{Q_4} = \omega R_{S4} C_4 \quad (16)$$

Where

$$\omega = 2 \pi f$$

R_{S4} = Series resistance at -4V

C_4 = Capacitance at -4V

If the depletion width at -4 volts is W, then

$$R_{S4} = \frac{\rho}{A} (W_{epi} - W) \quad (17)$$

With ρ being the resistivity, and

$$W = 3.4 \times 10^3 \left(\frac{4.6}{N} \right)^{1/2} \text{ cm} \quad (18)$$

Also

$$\frac{C_4}{A} = 8.5 \times 10^{-10} \sqrt{N} \text{ pF mil}^{-2} \quad (19)$$

(Units have been chosen according to current engineering convention.)

Substituting Equations (19), (18) and (17) into (16) yields the formula for the quality factor. However, we shall present this formulation under two points of view in the following paragraphs.

A. 1. 2. 2. 3 Optimized Design

The concept of optimization will necessarily differ from system to system. Some systems may require maximum tunability with less regard to insertion loss. Some systems, on the other hand, may need only a token amount of tuning but with maximum possible quality factor. As a general case, here, we assume for the optimization procedure the simultaneous maximization of breakdown voltage, V_B , and quality factor, Q . This simultaneous maximization dictates that the diode avalanches as soon as it depletes fully. Thus, we need to develop the interrelationships between doping concentration, epi thickness and diode area and a given set of V_B , Q and C .

To be practical and useful we should limit ourselves to the ranges of common usage. Namely

$$25 \leq V_B \leq 300V$$

$$1 \times 10^{15} < N < 3 \times 10^{16} \text{ atoms} \cdot \text{cm}^{-3}$$

$$300 \leq Q @ -4V \text{ and } 50 \text{ MHz} \leq 13000$$

$$003 \leq C/A @ -4V \leq 0.140 \text{ pF/mil}^2$$

The determining relationships, which have been all but completely developed in the above sections, can be written in the following form:

$$N = 2.143 \times 10^{18} V_B^{-1.33} \text{ atoms/cm}^3 \quad (20)$$

$$C/A = 8.5 \times 10^{-10} \sqrt{N} \text{ pF/mil}^2 \quad (21)$$

$$= 7.37 \times 10^7 \rho^{-0.585} \text{ pF/mil}^2 \quad (22)$$

$$\rho = 2.84 \times 10^{13} N^{-0.855} \text{ ohm} \cdot \text{cm} \quad (23)$$

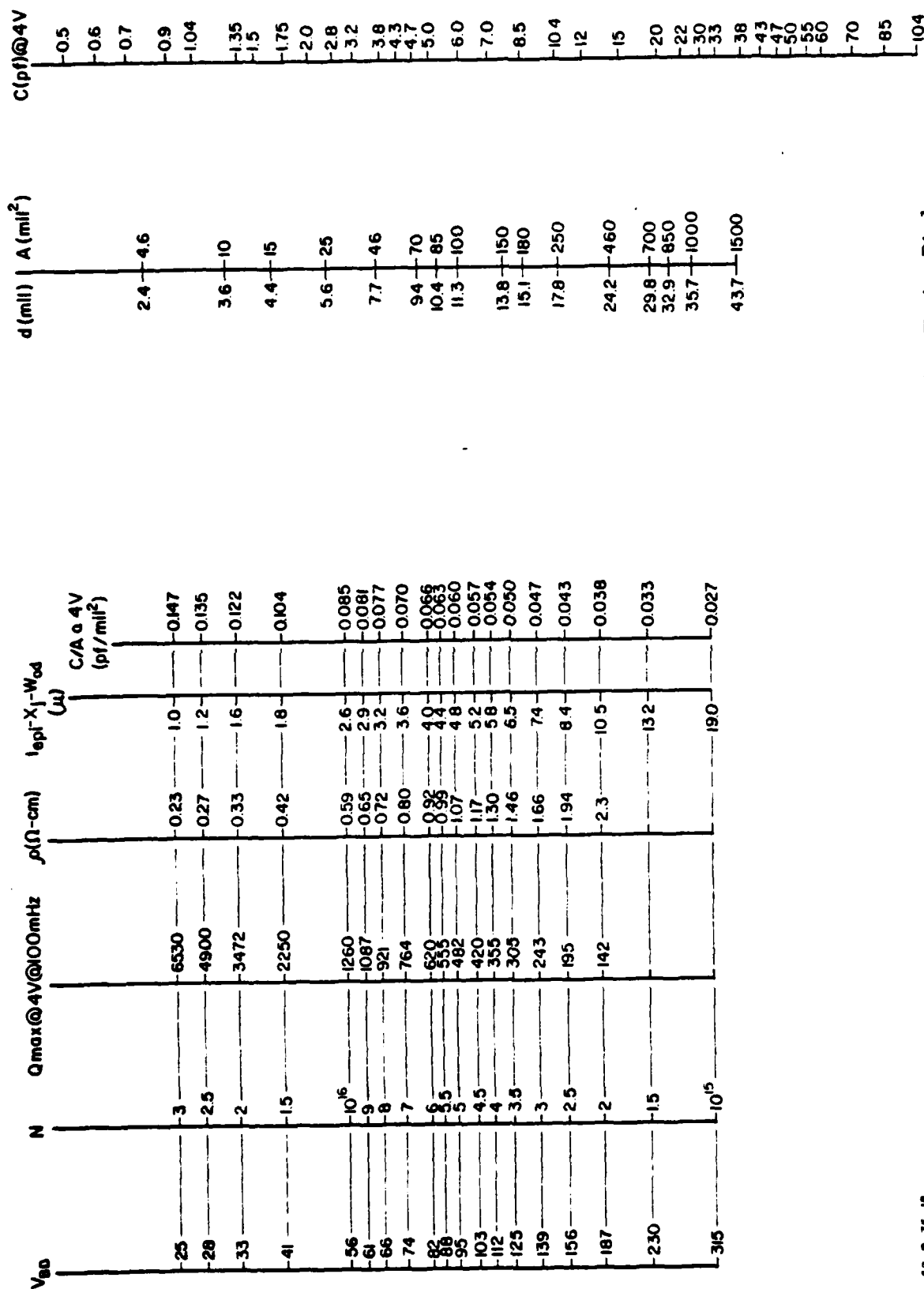
$$= 8.765 \times 10^{-3} (C/A)^{-1.71} \text{ ohm} \cdot \text{cm} \quad (24)$$

$$W_{\text{epi}} - (X_j + \text{Out diffusion}) = 0.0236 V_B^{1.17} \text{ cm}^{-4} \quad (25)$$

$$\frac{1}{Q_4} = 1.24 \times 10^{17} \left[N^{-1.2325} - 3 \times 10^{-7} N^{-0.855} \right] \text{ at } 50 \text{ MHz} \quad (26)$$

A design nomograph combining all these parameters is presented in Figure A-9. Procedure for using the nomograph is simple. Breakdown voltage specification is entered on the leftmost column (under V_B). Then moving on a straight line toward the right we obtain the maximum allowed doping concentration, N_{max} . Continuing to the right gives us the theoretical maximum Q (at 100 MHz which is 0.5 times that at 50 MHz). Ideally, the Q specification is entered on the Q column and the minimum allowed value of N , N_{max} , is obtained. The range for N to be specified can then be judiciously chosen.

Now a range defined by the specified values of maximum N and minimum N is formed and it is continued straight to the right until it intersects the capacitance per unit area, C/A , column. Then the capacitance specification range (at $-4V$) is entered in the rightmost column. Finally, using straight lines, the



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Figure A-9. Design Engineering Nomograph for Optimal-Abrupt Junction Tuning Diode

highest allowed capacitance and the lowest C/A reading to the lowest allowed capacitance, the intersection of these lines with the D/A (diameter/area) column gives the allowed variation in diode diameter/area.

A.1.2.2.4 Practically Optimized Design

In most applications the above optimization is more than necessary as it allows tuning all the way up to breakdown. It is quite common to have a requirement where the RF voltage swing occasionally exceeds the maximum DC tuning bias. In these situations one would have to have specified a breakdown voltage appropriately above the maximum swing voltage so that the avalanche mechanism does not fall within the tuning range. The new logic in a practically optimized design theory is such as to allow for a minimum epi thickness necessary to provide the capacitance swing with a doping level commensurate with Q and V_B requirements.

The governing equations undergo only a minor change to include the "new" fact that the breakdown mechanism is now limited by the epi thickness rather than the combination of thickness and resistivity. Note that the diode will now punch-through before breakdown. As before:

$$C \sim V^{-1/2} \quad (27)$$

$$W_{\text{epi}} = 3.4 \times 10^3 \left(\frac{0.6 + V_{\text{pt}}}{N} \right)^{1/2} \quad (28)$$

The punch-through voltage, V_{pt} , is taken to be the maximum tuning voltage. Thus, Equation (28) indicated that we have no more epi than is required for the capacitance swing. Now, if we choose the doping concentration, N, judiciously, we also satisfy breakdown requirements. The breakdown voltage for a thickness limited (truncated) epi is given by

$$V_B = E_{\text{crit}} W_{\text{epi}} - \frac{q}{2\epsilon_r \epsilon_0} N W_{\text{epi}}^2 \quad (29)$$

where E_{crit} is the critical electrical field initiating the avalanche mechanism. This field is dependent on the ionization rate as well as mean free path before recombination. A very good empirical formula describing the actual situation is:

$$E_{crit} = 4.1 \times 10^3 N^{0.125} \text{ V/cm} \quad (30)$$

Substituting Equation (30) into (29) and manipulating sufficiently we find the maximum allowed doping concentration, N_{max} .

$$N_{max} = 1.13 \times 10^{19} \left[\frac{(0.6 + V)^{0.5}}{V_B + 0.966 (0.6 + V_{pt})} \right]^{2.667} \quad (31)$$

To obtain Q we combine Equations (18), (17), (19) and (16) and solve for minimum allowed doping concentration, N_{min} .

$$N_{min} = 4.18 \times 10^{11} \left[Q_4 \left(0.46 \sqrt{0.6 + V_{pt}} - 1 \right) \right]^{1.17} \quad (32)$$

A mid-point, for example, between N_{max} and N_{min} can be used in Equation (28) to determine W_{epi} required. An incorporation of all the parametric equations in a nomographical form is presented in Figure A-10.

To use the nomograph:

- a. Start with the specified Q and go up vertically until the specified V -line is reached. The intersection point gives the minimum N we have to have to meet the specified Q and still have the required swing in capacitance.
- b. All the way to the left is the capacitance per unit area that this N will give us at -4 volts. From this number and the specified C_4 we obtain the area of the diode.
- c. Continuing horizontally to the right, we determine W_{epi} from the intersection of N -value and V -line.
- d. All the way to the right we observe the theoretical breakdown. Also on the same graph we have an arbitrarily drawn experimental breakdown curve (broken line) depicting a particular passivation system. If the broken line is not coincident with the solid line then, obviously, compromise is necessary and the quality factor will suffer.

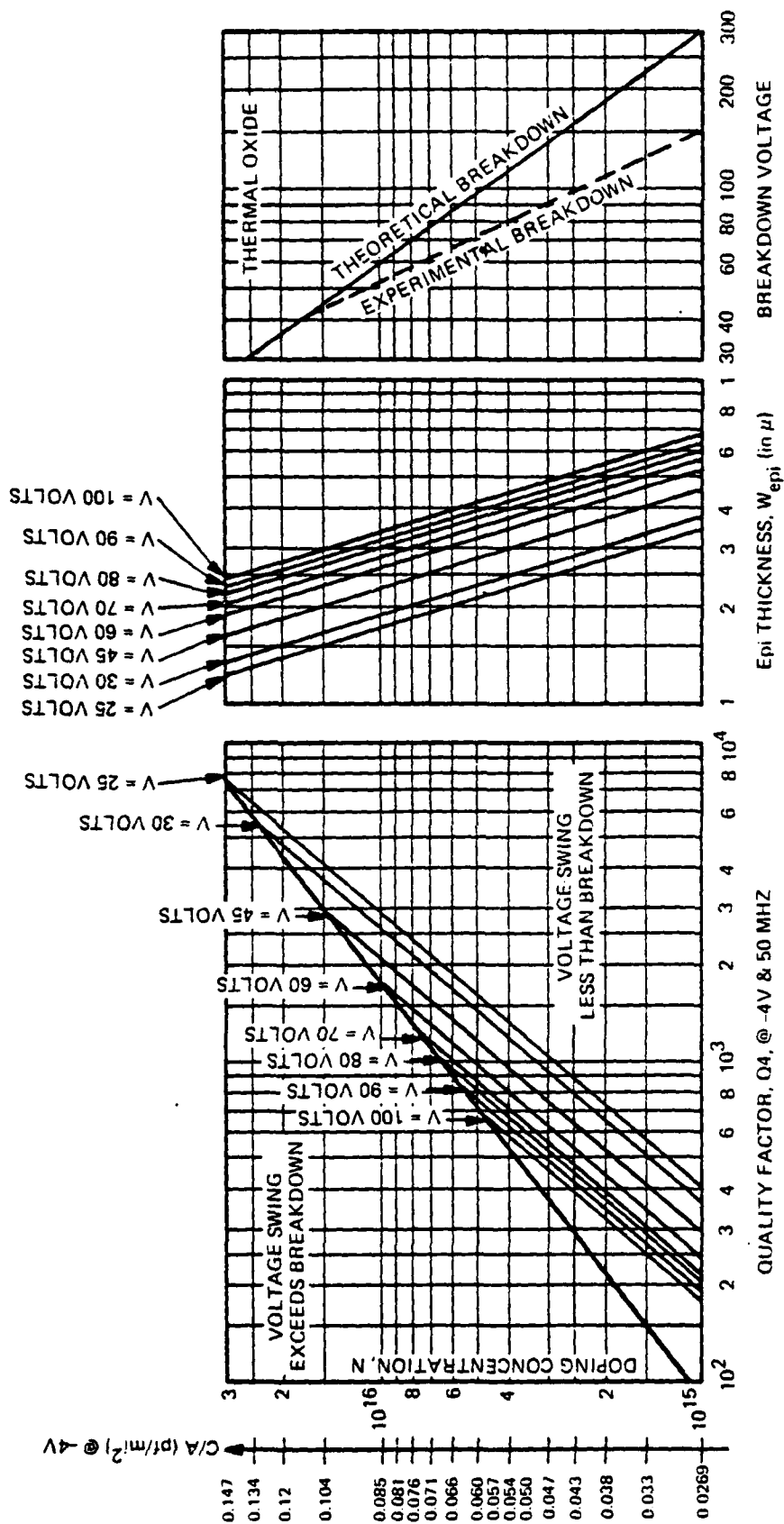


Figure A-10. Design Nomographs for Tuning Varactors with Truncated Epi

A.1.2.2.5 Deviations from Theoretical Behavior

As alluded to above, some deviations will occur from the predications given by theoretical analysis. This deviation almost always is in breakdown voltage. Apparently due to changes in the process conditions - most of which have remained unidentified - some degradation of the breakdown voltage occurs during the passivation step, utilizing, in particular, thermal oxidation. As an uncontrollable side effect of oxidation, uncompensated charged contamination is incorporated in the interface between the semiconductor and the oxide layer. The polarity of this charge is almost always positive in the case of oxide. Therefore, if the epi is n-type, an accumulation layer is produced on the surface modifying the conductivity there. The result is, of course, a degradation in the breakdown voltage. It should be noted in this regard that such surface-oriented degradation is not necessarily the course of every failure mode in the device but rather an indication of a non-ideal condition on the surface. Failure modes and their relationships to surface effects will be discussed in subsection A.1.5.

A.1.3 Detailed Processes - Fabrication of Microwave Diode Chips

a. PIN Diodes - The idealized doping profile of a PIN diode wafer is shown in Figure A-11.

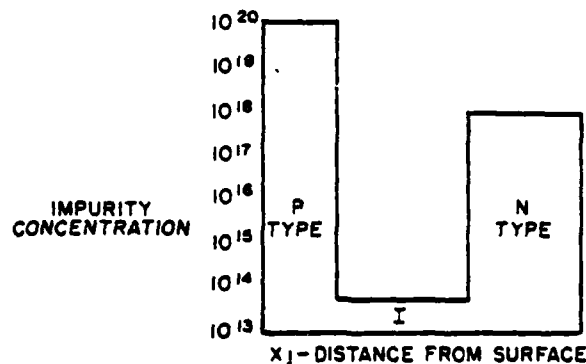


Figure A-11. Doping Profile

As can be seen, a heavily doped p-type region, and a heavily doped n-type region surround an "intrinsic" (more realistically, a slightly n-type) region whose volume determines many of the diodes' performance characteristics.

PIN diodes, depending on the application, whether a switch, attenuator, or limiter for example, are usually specified by voltage breakdown, capacitance (at zero bias, or some other bias voltage), R_s (at 10 or 100 mA), forward voltage, reverse leakage current, and lifetime. Chip size will be dictated by package considerations. The I-region thickness and junction depth will determine breakdown voltage, and the area of the junction and I-region thickness will determine the capacitance. Punch-through voltage is dependent on the resistivity and I-region thickness, and R_s will depend on the minority carrier lifetime, resistance of the swept out region, resistance of any residual unswept region, and contact resistances to the heavily doped n^+ and p^+ regions. If all other resistances are minimized (or negligible), the main contributor to the R_s for a PIN diode may be represented as

$$R_s \cong \frac{W^2}{2\mu\tau_{eff}I_f}$$

where

W = final I-region thickness

μ = effective mobility $\cong 600 \frac{\text{cm}^2 - \text{volts}}{\text{sec}}$

τ_{eff} = effective minority carrier lifetime

I_f = forward current

From a design point of view, the diode chip can be determined, then, by deciding on a certain final I-region thickness, chip size and junction area; the other parameters, such as contact resistance and minority carrier lifetime really are results of selection of the optimum process. Let us consider a process for fabrication of a microwave PIN switch. We have been presented a specification of the following type:

V_B at 10 μ amps = 35 volts min

C_T (at -20 volts) = 1.0 pF max

$$T_L = 100 \text{ nsec max}$$

$$R_s = 0.5 \text{ ohm max at } 10 \text{ mA}$$

Package style dictates a chip no larger than 30 mil^2 . Gold metallization is preferred by the customer. One can measure the capacitance of an empty glass package and, after subtracting this from the total capacitance listed in the specification, one arrives at the design capacity value for the chip. A calculation based on the well-known equation

$$C = \frac{K\epsilon A}{W}$$

where

A = junction area,

W = final I-region thickness (dictated by V_B),

K = permittivity,

ϵ = dielectric constant

leads one to the correct mask dimension to be used during fabrication. Since the capacitance is specified at -20 volts it is desirable that the depletion region punch through at voltages much less than this bias. A relationship can be derived using an abrupt junction approximation relating the bias voltage, depletion layer width, and background concentration. This relation is given below:

$$C_B = \frac{2K_s \epsilon_o V_{(PT)}}{qW^2}$$

We can refer to the bias voltage as the punch-through voltage in this case, and W as the punched through depletion layer width. C_B is the background concentration in atoms/cc. We can tabulate, for various background concentrations and assumed punch through voltages, the amount of spread of the depletion region, so as to arrive at the optimum starting resistivity. This data is presented in Table A-5 (assume lightly doped n-type material).

TABLE A-5.

CASE - I: Zero Bias Punch-Through

<u>Resistivity</u>	<u>Doping Concentration</u>	<u>Atoms (Parts/ Billion)</u>	<u>Depletion Layer Width (Microns)</u>
500 ohm-cm	1.3×10^{13} atoms cc	0.2	7.4
200 ohm-cm	2.5×10^{13}	0.5	5.3
100 ohm-cm	5×10^{13}	1	3.8
50 ohm-cm	1×10^{14}	2	2.7
5 ohm-cm	1×10^{15}	20	0.6

CASE - II: 2 Volt Punch-Through

<u>Resistivity</u>	<u>Doping Concentration</u>	<u>Atoms (Parts/ Billion)</u>	<u>Depletion Layer Width (Microns)</u>
500 ohm-cm	1.3×10^{13} atoms cc	0.2	15.4
200 ohm-cm	2.5×10^{13}	0.5	11.1
100 ohm-cm	5×10^{13}	1	7.9
50 ohm-cm	1×10^{14}	2	5.5
5 ohm-cm	1×10^{15}	20	1.7

Usage of the above table (or better, similar data plotted with W as a parameter) indicates that the higher resistivities are necessary for reasonable depletion layer widths at low voltages. Since the breakdown voltage of a PIN diode is related to the 'I' region impurity concentration, as well as thickness, the voltage breakdown specification will set a minimum final thickness, and the punch-through voltage

determines a minimum resistivity. The maximum electric field for high resistivity silicon is approximately 33 volts/micron. Using the relationship for an abrupt junction -

$$E_{\max} = \frac{2 V_B}{W}$$

one can arrive at the conclusion that to support a 50-volt breakdown, a minimum 3.4 microns of intrinsic region is necessary. Reviewing the preceding tables concerning V_{PT} (especially if we were dealing with a difficult R_s specification where low punch through is necessary), we observe that 100 ohm-cm is the minimum resistivity which would allow zero bias punch through, and 50 ohm-cm would suffice should we be able to allow a 2-volt punch through for this V_B specification allowing for a 2.0 microns diffusion into the layer, starting material would be specified as 6 microns of 100-ohm-cm epitaxial silicon on a heavily doped silicon substrate. A batch of 10-20 wafers is then drawn from inventory, the characteristics of layer thickness, Copeland profile, and substrate type recorded on the lot traveler. Reference is made to the epitaxial run number, date and substrate lot, so that silicon traceability is obtained. The lot arrives at the cleaning station, where the silicon wafers are subjected to solvent and acid cleansing. Organic residues, oils, dust and dirt are removed at this point; in addition, metallic contamination and organic residue from the solvent cleaner are removed. The wafers are then thoroughly rinsed in deionized water, and dried.

Immediately, the silicon wafers are loaded into boats and inserted into a high temperature oxidation furnace. Approximately 5,000 Å of thermal oxide is grown on both sides of the wafer. The wafers are withdrawn, allowed to cool in closed containers, and the oxide thickness is measured on a control wafer which accompanied the run. At this point, the process becomes different, depending on whether a planar or mesa device is desired.

The two paths differ as follows:

<u>Planar</u>	<u>Mesa</u>
Oxidized Wafers	Oxidized Wafers
↓	↓
Photolithography	Strip Oxide, High ρ side
Clean	Clean
Boron Deposit	Boron Deposit
Boron Diffusion	Boron Diffusion
	Photolithography
	Mesa Definition
	Mesa Formation

For the planar technology, the photolithographic step is determined by the junction area needed to provide the correct capacitance after diffusion and the chip size is based on package requirements, any thermal resistance considerations, and optimum packing densities on the wafers. Thus, a mask of XXX mils on YYY mil center-to-center would be ordered, and the image would be referred to as a positive mask (if negative photo result is used). The result would be a hole of XXX mil diameter and YYY mil center-to-center, cut into the thermal oxide after appropriate hydrofluoric acid etching. Each wafer would receive identical treatment, being batch processed whenever possible. Spinning and aligning, however, are individual steps and require individual wafer handling. After inspection of the wafers for appropriate dimension, and completeness of etching, as well as masking oxide integrity, the wafers are immediately cleaned and placed into the furnace for boron deposition. Times and temperatures to assure a 2-micron diffusion for this device are provided on the lot traveler. Sheet resistance controls are listed on the lot traveler, and satisfactory furnace performance is assured by measuring sheet resistance on a monitor wafer. The wafers are removed from the furnace, cooled in a closed container, and at this point are ready for their first electrical dc performance check.

In the mesa process, the masking oxide is stripped completely from the high resistivity side of the wafer. After undergoing a cleansing and rinsing operation, the wafers are dried and immediately placed into a high temperature boron deposition furnace, again with times and temperatures determined to allow a 2 micron diffusion. Sheet resistance is monitored as in the above planar process. The wafers are then removed, cooled and sent to photolithography. At this point dc statics can not be measured, as the junction extends over the entire wafer, continuously. The photo-resist application from the point of view of determining the final chip size and junction area requirement is similar to the above. However, the opposite image is used, i. e., negative, for negative photo-resist. Thus, rather than opening a hole through a film, we are leaving a masking dot of the appropriate dimension on the surface. This dot will define the mesa top, and thus, the junction area.

(A word on photo-resist types might be useful: photo-resists are referred to as positive or negative, depending on the type of interaction with ultraviolet radiation. Negative photo-resists are those which are polymerized when exposed to this radiation. Positive photo-resists are those whose polymeric chains are formed during the prebaking operation, and are broken down by the effect of ultraviolet radiation. In both cases, the nonpolymeric species is soluble in suitable solvent, while the polymeric species remains impervious to solvent action. Prolonged exposure to solvent in aqueous treatments, or standing in humid atmosphere, can affect the ability of the photo-resist to withstand these solvents, however.)

After the mesa is defined by photo-resist, it is necessary to form the mesa by silicon etching techniques. Generally, batch mixtures of nitric, hydrofluoric and acetic acids are used with the formulation depending on the etch depth necessary, and the etching rate desired. Since the diffusion depth is known, and the original 'I' region thickness is also known, it is only necessary to etch to a depth which ensures etching through the 'I' region, into the n^+ substrate, to prevent 'I' region exposure at the dicing operation. 'I' region exposure causes increased leakage currents paths and premature device failure. Once etching is completed, the mesa slice is now able to be probed for dc statics.

It might be noted at this point that the breakdown voltage observed for the same diffusion into similar material done by planar and mesa techniques is not the same. In the mesa situation, the junction front indeed approaches a plane junction. In the planar junction, lateral diffusion at the edges of the diffusion window results in anything but a plane junction. Thus, pictorially,



A reduced value of breakdown voltage will be observed for the planar junction because of the finite radius of curvature of the junction. Increased fields in the areas of the junction radius will cause the critical field to be reached earlier, thus breakdown will occur at those areas. This fact is normally taken into account in designing a PIN diode, when addressing the V_B specification. However, to go to a thicker 'I' region to assure higher breakdown may cause trouble in meeting capacitance or R_s specifications. Thus, the tradeoffs between device types come into play in the design aspect of the device.

At this point, similar operations are performed on either the planar or mesa device. They are listed below:

- Thermal Oxidation
- Photolithography
- Thickness Etching

- Contact Metallization
- DC Evaluation
- Dicing

Thermal oxidation is performed after boron diffusion for two reasons. Improvement of subsequent etching of the contact window by redistributing the heavy concentration of dopant at the surface, making the phase more soluble in the etchants used, is a prime consideration. Also, additional protection and stabilization of the junction is provided by additional oxide, especially where a contact will be cut in the original oxide. Generally, the temperature at which this oxidation is carried out is lower than the original cycle, so as to minimize movement of the junction. Wafers are oxidized in a batch; either standing or laying flat, in a quartz or silicon boat.

After thermal oxidation, the lot is ready for photolithography to reopen a hole or clean oxide from the top of the mesa. The contact hole must be centered within the diffusion window and must be etched completely to the silicon surface. The photo-resist layer is then stripped, and the wafers are immediately transported in closed containers to the metallization step, where they are cleaned thoroughly. Metallization consists of applying a film of metal element onto selected areas of the wafer with sufficient binding energy so that intimate contact with the heavily doped region of silicon is achieved. The contact must be "ohmic", that is to say, linear in its electrical behavior, and not add additional impedance to the device characteristics. In addition, the adhesion of the metal contact must be adequate to withstand bond pull tests as required in the specifications. Poorly made contact metallizations will show up in device performance as contact resistance, contributing to R_s (or insertion loss) increases, thermal resistance, and mechanical yield. Gold is often used as the metal to which bonding in the external circuit will be performed. Gold, however, has the chemical characteristic of forming a eutectic compound with silicon at temperatures near 300°C. Thus, a barrier metal, or metals, is necessary to prevent the silicon-gold reaction from occurring. Refractory metals fulfill this function. Techniques for

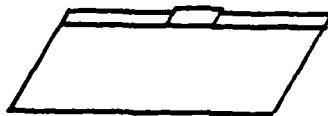
application of these metals include RF sputtering and electron beam evaporation. Each technique has its own advantages and disadvantages insofar as ease of application, adhesion characteristics, and side effects. For example, RF sputtering provides superior adhering films, but also can cause radiation damage to occur (electron-hole traps are formed in the oxide, for example). Also, step coverage in sputtered films is excellent. Electron beam evaporation (or even filament evaporation) provides a less energetic source for metal deposition, with the resultant lessening of adherence qualities. Step coverage is that expected from a point source, so that carousels and planetary action might be needed to improve this situation. Commercial vacuum systems are used in the metal deposition steps.

Vacuum is provided by either oil diffusion pumping, backed by mechanical pumps, ion-pumping, or cryo-pumping. The latter two techniques are considerably "cleaner" techniques, as the oil diffusion pumping leads to the possibility of contamination of the bell jar through oil molecules backstreaming into the chamber. Often, large surface area cold traps are inserted between the oil diffusion pump and the bell jar; these are liquid nitrogen cooled, and will freeze out impurity molecules as they attempt to migrate into the chamber. Background composition within the bell jar is normally monitored by means of mass spectrometers (called residual gas analyzers) permanently attached to the system. Hydrocarbons, water vapor, nitrogen can be easily identified by their mass peaks in an analysis sample. Monitor wafers and glass slides accompany a material lot to provide adhesion, thickness, and contact resistance information, as well as establish metal-etching rates and characteristics. Specific contact resistance for many of the metals deposited on clean, heavily doped silicon, is of the order of 10^{-6} ohms-cm². Thus, the quality of the metal film deposition can be monitored electrically at this point by observing the actual contact resistance measured.

The wafer lot, after metallization, is sent for dc static testing, and capacitance and lifetime measurement. Voltage breakdown, forward voltage, and, where possible, leakage current are measured at this point. In addition, capacitance voltage relations are determined (measured usually at 100 MHz) and minority carrier

lifetime is determined. Production approval for the lot is given when the above parameters are within the desired specification. Wafers are rejected if any parameter falls out of specification, as there is no recovery technique available at this stage. Approval or rejection is generally on a wafer-to-wafer basis, rather than the entire lot.

The final step in the chip fabrication is the dicing operation. Wafers are mounted by some means (either wax, vacuum, freeze-down) on an appropriate dicing system. This may be a diamond scribing machine, a diamond saw, or a laser scribing machine. These have the purpose of separating the individual chips of the correct dimension from the wafer. Diamond scribing generally involves applying a stress front into the wafer by means of a diamond-stylus and then in a subsequent step fracturing the wafer which breaks down the crystalline planes. For $\langle 111 \rangle$ type material, scribed chips have the cross sectional shape of a parallelogram, i.e.,



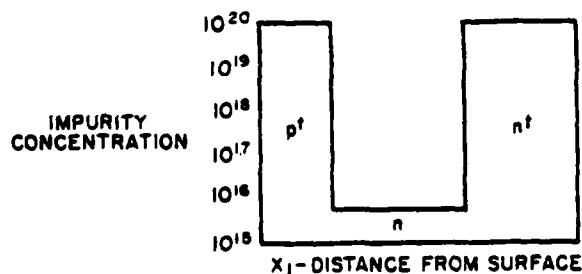
showing the cleavage of the wafer along the planes. On the other hand, sawed chips and laser scribed chips are rectangular in cross section, which demands different handling in subsequent automatic die mounting equipment.

Laser scribing is a relatively new technique, where the silicon is vaporized by a high intensity laser beam which is indexed along the wafer. A protective coating is applied to the wafer prior to scribing, to prevent contamination and laser "splash" from degrading the electrical performance. This protective coating, as well as any waxes or adhesives used for mounting and holding the wafer must be removed by a series of organic solvent cleansing of the chips, in combination often with ultrasonic vibration. One must be careful, however, of introducing mechanical damage by the ultrasonic treatment, and must use appropriate power levels. For that matter, mechanical damage can be introduced during any of the three above mentioned dicing operations, leading to raggedness, chipping and microcracks, which will eventually cause device failure during life testing. The scribed, cleansed chips are then placed in a sealed container and a sample is run for mechanical and electrical

yield, to include RF testing where necessary. Resistance, switching speed, total capacitance, and voltage breakdown determine the nature of the diode; as in most microwave circuitry, however, the actual proof is the circuit performance of the diode. Often, a small difference in lifetime from lot-to-lot, or a slightly greater leakage current from lot-to-lot, could cause the device not to perform optimally in the circuit, despite the fact that the DC and RF specifications were met. Many times, explanations of this behavior can be found in terms of slightly different parasitics, bond wire length, package capacitance, etc., when the real reason is found within the chip itself. The degree of control necessary to assure high yield from slice to chip to circuit performance has not been available to date, despite the many controls presently used.

b. Tuning Varactor - As the name implies, a tuning varactor is a variable capacitance, nonlinear element; the capacitance varies as a function of applied bias voltage, ideally inversely as the square root of the applied voltage.

The fabrication of tuning varactor wafers at many steps in the process is similar to the above discussed process for the PIN wafer. The difference lies mainly in the use almost solely of the mesa construction, the difference in the starting material epitaxial layer, and the shape and magnitude of the capacitance-voltage relationship. The doping profile of a tuning varactor wafer can be shown to be the following:



As shown, we have a $p^+ - n - n^+$ structure, when n in the epitaxial layer is in the order of 1 ohm-cm. Here, much care is used in the depositing of the doped epitaxial layer, in that significant operational performance differences will be observed for differences in the first decimal place of resistivity; thus 0.5 to 1.2 ohm-cm represents doping concentrations of 7×10^{15} to 4.5×10^{15} atoms-cc and 2 ohm-cm represents 2.5×10^{15} atoms-cc. This threefold difference in doping concentration affects breakdown voltage and capacitance/area for these devices and thus must be as precisely identified as possible to design a tuning varactor to the highest figure of merit (Q factor). Thus, the diode chip must be designed such that breakdown occurs close to, but not as, the depletion layer punches through so as to leave no unswept resistive layer within the epitaxial layer. Punch through of the depletion layer cannot be allowed at a lesser bias voltage because of capacitance swing and tuning considerations. Many tuning varactors are operated near breakdown voltage so that "over-designing" from a layer thickness and V_b point of view is not possible, as this technique would serve to decrease the Q factor. The layer is then specified so as to provide optimum V_B , square-law variation of capacitance with applied bias voltage, in the correct capacitance range, on a low resistivity substrate. For example, we might specify a 5-micron, 0.8 ohm-cm (7×10^{15} atoms-cc) to be grown. This doping concentration would provide us with a voltage breakdown of 74 volts. Assuming a 2-micron diffusion we would be left with 3 microns of epitaxial material, having calculated that at this breakdown voltage and doping concentration, the epitaxial layer thickness should be about 3 microns from the relationship.

$$\begin{aligned}
 W &= \sqrt{\frac{2K, \epsilon_0 V}{q C_B}} \\
 &= 3.4 \times 10^3 \sqrt{\frac{V_{total}}{C_B}}
 \end{aligned}$$

The capacitance is usually specified at -4 volts so that the capacitance per area can be calculated at this bias voltage, which then defines the mean diameter and function area necessary to provide this capacitance. For example, the wafer is described

would have a capacitance per area of 0.07 pF/mil^2 . Thus, a mesa or junction area of approximately 70 mil^2 would be needed for a tuning varactor having a capacitance of 5 pF at -4 volts.

Processing the wafers then becomes, stepwise, similar to the mesa PIN process. Thermal oxidation, followed by oxide stripping of the epi side, 3-micron boron deposit and diffusion, at an intermediately high temperature would take place. The junction should be as abrupt as possible to allow square-law behavior of the C-V characteristic. Surface concentration and substrate concentration have to be high enough (virtually degenerate material) to allow negligible contact resistance to be observed. Excessive contact resistances could also degrade Q. Q is defined as:

$$Q_{(-4)} = \frac{1}{2\pi f R_{(-4)}} C_{(-4)}$$

and contact resistance would show up in R_s .

After boron diffusion, photolithography defines the mesa by the appropriate dimension necessary for the desired capacitance at -4 volts. A positive mask is used, with negative photo-resist, leaving a dot of photo-resist whose dimension defines the mesa.

By means of a silicon etch, the mesa is now etched into the silicon, and capacitance and voltage breakdown are monitored as the etching proceeds. When the desired value at the bias voltage is obtained, the wafers are cleaned and thermally oxidized for passivation. Photolithography again clears the oxide from the mesa top. The wafer is thinned to an appropriate thickness for later dicing, and metallized on both sides. After a final dc check for V_B , V_f , and the C-V characteristic is determined, the wafer is either approved for dicing or rejected. Approved dice are evaluated on a sample basis for V_B , C-V, and Q is measured (usually at 100 MHz). Everything which was said earlier relative to dice cleanliness and surface condition is equally important for tuning varactor chip fabrication. Surface contamination or unwanted charges in the thermal oxide passivation can lead to tuning difficulties, post-tuning drift, instability or degradation of breakdown voltage and lower Q values.

In short, the surface condition of either a PIN or varactor chips is equally important from an operational point of view.

A.1.4 Traceability and Test Points

During the processing of microwave semiconductor devices, traceability and complete history of each event that occurs affecting the starting silicon material is very difficult. Equally difficult are the chemical and electrical evaluations at each step in the process, which could indicate the success or failure of a particular process step. It follows, therefore, that failure of a device in a circuit, or in a life test prior to insertion in a circuit, is not traceable as to the cause or possible process step where a latent failure mode was incorporated. The present program then has as a goal the capability of establishing as total and complete a historical record as possible, so that by improved and monitored controls and tests throughout the process, yield information is directly obtained and a correlation made with measured impurity types and levels.

Presently in a typical production area, traceability for the silicon itself is probably quite good. Thus, ingot and substrates are identified and coded; doping levels (resistivity) and dopant type are well identified. In some cases, bulk lifetime has been measured and recorded for the ingot. Likewise, the silicon epitaxial layer can be well characterized electrically and dimensionally. Resistivity, by four-point probe methods, Copeland profiling and/or differential capacitance measurements for doping concentration as a function of layer thickness, infrared reflectance, or angle lapping and staining for layer thickness are all available and much used techniques. Processes for cleaning, polishing and slicing are usually well documented as to dates, procedures, times, temperatures, and operators. A glaring weakness: since chemicals and gases are often batch mixed, delivered by long lines through flow meters, or heated in beakers, usually in open air, chemical lots and purity levels are lost and do not form part of the historical base. This weakness cannot be blamed on the chemical or gas supplier: they purify their chemicals and gases to the levels specified. However, they do not guarantee anything about

homemade receipts for batch processing and mixing chemicals. Often the chemicals are mixed in open air, in beakers which have been cleansed in the same chemicals, and rinsed in deionized water, the analytical content of which is not continuously known; or monitored. Although chemicals are usually delivered from the suppliers with lot numbers assigned, rarely does the lot number become part of the recorded history for the device manufactured, and in fact, it becomes rather meaningless when two or three types of acids are mixed, as in the silicon etches. Gases, likewise, are delivered in cylinders whose history is probably unknown. Analytically, the gas has been characterized after pressurizing the cylinder. Impurities desorbing from the cylinders, or entering from reactive materials or leaks in delivery lines and connections, flow meters, presently go unidentified and undetected, being hidden in the yield of that process step.

Once wafers begin the fabrication part of the process, traceability becomes much less. Although lot cards list processes, dates, and operator identifications, wafers constantly interact with other lots of wafers, large batches of mixed chemicals, different lots of gases, and gas mixtures, quartzware which has been cleansed in other mixtures of similar chemicals, so that conventional historical recording only scratches the surface. The hypothesis is that if the silicon is maintained under the most controlled conditions, the ambient clean and constant in humidity and temperature, the proper techniques used (with the best chemicals and gases available, in high purity quartz containers), and the design engineers knowledgeable to "hit" the specification, that the yield from wafers into devices shipped should be at least constant (although low). The processing requirements mentioned above, however, add considerable manufacturing cost to these devices because of the high capital investment necessary to provide the proper environment and high materials costs because of the extreme purity necessary in the chemicals, gases and other materials. And yet the production yields typically are no greater than 7 to 8%.

The objective of this program is to realize the next order of magnitude of control, monitoring subtrace impurity levels and all other physical and chemical

parameters which could result in improved yields through better insights into the processes based on quantitative data. The improved yields should impact government spending in these areas by lower costs per unit.

A.1.5 Failure Mode Analysis

Failure mode identification, diagnosis and prognosis are, of course, three essential elements of corrective engineering. Accordingly, we will present, in this subsection, analytical comments on key modes of failure affecting semiconductor devices. In each case we will point out the distinguishing feature of the failure mode under study.

A.1.5.1 Breakdown Voltage Degradation - This mode of failure exhibits itself as a reduction in the ultimate breakdown voltage capability of the device. We distinguish, here, those causes where catastrophic "shorts" occur within the device. The tuning varactors in particular suffer from such degradation. A PIN diode's breakdown voltage is limited mainly by the I-region thickness, and the processing that the diode undergoes does not affect that thickness. We are obviously excluding here radius of curvature type limitations since such limitations are natural and hence do not constitute a failure.

In PIN diodes, if breakdown voltage degrades it is usually catastrophic. On the other hand, in a tuning varactor, as we have seen in subsection A.1.2, the breakdown mechanism is very much determined by the carrier concentration levels and, therefore, any modulation in conductivity during processing will affect breakdown voltage. The particular process step where a reduction in V_B occurs is the oxidation (passivation) step. Reduction, when it occurs, is evident when post-oxidation measurements are compared to pre-oxidation readings. Mesa structure is recommended for breakdown voltage testing as radius of curvature effects will be eliminated; of course, the necessary precaution needs to be taken when making the V_B measurements on a bare (unpassivated) junction. However, this is certainly not insurmountable for the experienced engineer who can easily identify the true avalanche region.

Breakdown voltage degradation, therefore, is a failure mode, the detection of which tells us of a process problem in the case of tuning varactors.

A.1.5.2 Leakage Current Increase - This mode of failure is not uniquely identifiable unless a "standard" is known. Namely, the leakage current, I_r . Readings in the pre-oxidation phase are not accurate due to the exposed conditions of the junction. Thus, a comparison of such readings with the post-oxidation readings does not provide a meaningful failure analysis tool. However, one can intentionally and controllably change the process conditions and then compare I_r readings at the post-oxidation step. This does provide a relative but nevertheless a comparative failure analysis tool.

Under ideal conditions (i.e., perfectly clean and undamaged silicon surface) the leakage current will be determined by a recombination-generation mechanism. This mechanism is exacerbated by various means: one is the undesired addition of contaminants into the passivation during processing. These contaminants may or may not be in a charged-ionic state which will then affect V_B in a tuning varactor. If they are not charged, then they will constitute an "alien" site in an otherwise crystalline/amorphous (Si/SiO_2) interface where they may act as additional recombination-generation sources. Another means is the "awakening" of some impurities within the bulk which become active as a recombination-generation source during processing. Usually, however, there are annealing steps which alter bulk conditions but not surface conditions. By applying such steps one can qualitatively identify contamination on the surface.

Observing leakage current close to avalanche (but not at avalanche) for a sufficiently large number of wafers after each closely controlled process step enables us to identify "trends" in process-induced surface degradation.

A.1.5.3 High Temperature Reverse Bias (HTRB) Induced Failures - HTRB-induced failures are perhaps some of the most diagnostic. At excessively high temperatures such as 200°C and at applied biases of about 90% of breakdown, the failure mechanisms become quite accelerated. The electric field is high and mobility of impurities (on the surface or in the bulk) is high. Under these stress conditions contaminants and impurities readily move.

The important thing to observe is the mode of failure that occurs in HTRB stressing. If the devices become electrical "shorts" then the most likely candidate is improper metallization or non-ideal crystalline structure under the metal layer. Metal propagation into silicon through damaged sites in the silicon will cause shorts. Such failures will occur rapidly in shallow junction devices. Prior to shorting, however, the leakage current behavior is not affected.

Leakage current in semiconductor devices should increase with temperature at a rate of approximately 10% per degree centigrade. This law is true for bulk recombination-generation mechanism. The surface component of the recombination-generation process dominates in almost all cases with no contamination on the surface. Therefore, we cannot look at the temperature variation of leakage current and hope to identify the existence of contamination on the surface. However, once a certain temperature level is reached, the leakage current of an uncontaminated device should be time-invariant. Any tendency in I_R to change with time is a clear indication of the existence of contamination. How fast this change occurs is only a measure of the level of contamination and/or its mobility at that temperature and electric field.

The usual manifestation of this kind of HTRB-induced, leakage current-oriented failure is "channeling." Although some ionic contamination will "relax" back, after HTRB, most of it will have moved irreversibly under the difference of the electric field, to cause channeling.

Channeling is a direct result of contamination and, as such, it is a unique means of identifying process problems. It should be recognized that even though existence of channeling tells us there is contamination, its absence does not tell us the opposite. Hence, "pre-HTRB" and "post-HTRB" comparison of I-V characteristics of the diode is absolutely imperative.

A.1.6 Chemical Contamination

Chemical contamination of semiconductor materials occurs intentionally or non-intentionally during the same process. Doping of a silicon ingot, epitaxial layer or diffusion layer to a certain resistivity level is an intentional introduction of

controlled amounts of impurities so as to modify the electrical nature of the silicon. Often, however, accompanying the introduction of these specified impurities, are unwanted impurities, in concentrations sufficient to provide modification of the electrical characteristics which we originally desired. Table A-6 contains a list of many of the elemental impurities which beneficially or adversely affect silicon, and the type of effect which they are thought to have.

TABLE A-6. ELEMENTAL IMPURITIES AFFECTING SILICON

<u>CONTAMINATES WHICH DOPE SILICON, ELECTRICALLY ACTIVE</u>	<u>HEAVY METALS, "FAST DIFFUSERS", AFFECT LIFETIME AND V_B</u>
Aluminum	Gold
Antimony	Iron
Arsenic	Copper
Boron	Mercury
Gallium	
Mercury	<u>ALKALI METALS, AND OTHERS WHICH DIFFUSE IN SiO_2</u>
Oxygen	Sodium
Phosphorus	Lithium
	Cesium
<u>CONTAMINATES WHICH FORM OXIDES</u>	Potassium
Transition Metals; e.g.,	Hydrogen Ion
Nickel	
Molybdenum	<u>HALIDES, WHICH CHEMICALLY REACT WITH SILICON</u>
Palladium	Chlorine
Silver	Fluorine
Tin	Bromine
Zinc	Iodine
Chromium	
Cobalt	

Generally, contamination of silicon occurs either within the crystalline lattice of the silicon itself, within the silicon dioxide protective layer on the silicon surface, or is trapped at the interface of the Si/SiO₂. With the lattice, contamination may be of a substitutional or an interstitial nature, depending on the thermal energy (i. e., temperature) which the contaminating species had acquired during ingress. Once in position and "frozen" within the structure, the effect is that local fields are set up, usually referred to as trapping centers, or recombination centers, wherein minority carriers are trapped. For example, gold has a solubility in silicon of approximately 10^{16} atoms/cc at temperatures near 1,000°C. Once gold has diffused substitutionally, it will freeze out minority carriers to a doping level which is approximately equal to the number of substitutional gold atoms, thus drastically increasing the resistivity of the silicon. Although this effect might be beneficial toward manufacturing a zero bias punch-through device, the higher resistivity of the epitaxial layer would have a detrimental effect on series resistance of the diode under forward bias, and since dissipative losses are increased by the increase in R_s , power handling of the device is degraded.

Avenues for the introduction of these contaminants into the semiconductor material appear in any step in the process, as well as from the environment and handling of the wafers.

Any of the reagents which are used have to be assured to contain metallic impurities within their specification maximums. Sodium is probably the most difficult element to exclude from the process facility and reagents. Exposure of a junction during mesa etching to acid mixtures, deionized water rinses, and ambient conditions provides a relatively easy ingress to such metallic contamination. Migration of certain elements through diffusion tube quartzware at elevated temperatures, or back streaming of airborne contamination into an oxidation tube provides not only ingress to the contaminating species, but also the temperature required to drive the contaminant into the silicon lattice or oxide film. Finally, the handling of the wafer material throughout the process by metallic, plastic, or teflon coated tweezers, vacuum pickups and carriers, as clean as they may be, has to be considered potentially damaging to the electrical performance of the wafer. Metallic

particles, within the micron dimensions, are sufficient to degrade not only wafer performance but also processing equipment. These particles can originate from worn tweezers, from joints in gas delivery lines, from being transported by gas flows, and from an abundance of other sources. These particles adhere to the surface of the wafer, and are not removed by many cleansing operations. Then at high temperatures they are driven into the lattice to provide a mechanism for device failure.

The most obvious routes for contamination to occur for silicon is through the frequent immersions of the wafers in acids, solvents, and deionized water. Silicon etching, for mesa formation, is normally carried out in mixtures of nitric, acetic and hydrofluoric acids. The particular formulation used is dependent on the etching rate and depth required. Certain formulations are also available commercially; e.g., 6-1-1 (6 parts nitric, 1 part acetic, 1 part hydrofluoric acid). The particular formulations used in-house are mixed in batches in the chemical mixing area. They are then withdrawn from stock as needed. The chemical impurity content then, for that particular lot, is unknown.

Solvent cleaning is performed with hot trichloroethylene immersions, followed by methanol and acetone rinses - oxide etching is done by hydrofluoric acid and ammonium fluoride. All acid operations are followed by rinses in cascading deionized water. Doping is performed with boron tribromide, and with phosphorous oxychloride.

The preceding named reagents are obtained from the vendor who specifies the maximums for the particular lot purchased. Emphasis is placed on the fact that the analysis is a lot analysis, and not an individual bottle analysis. After the lot has been analyzed, it is either shipped by rail car, or dispensed into individual containers through various transfer lines, and sealed, for delivery. These containers are barrels, bottles, cans and tank trucks. Analysis is not generally performed on individual containers, although samples are undoubtedly taken. Contamination or variation in levels of contamination can occur in the transfer of chemicals through the manufacturer's delivery system, despite their own controls. Examples of the types

of lot analyses reported by the vendors for selected acids, solvents and doping sources, used within Microwave Associates for their standard production processes, are given in Table A-7.

A glance at the specifications for any of these high purity chemicals shows several things: they are far from being free from foreign species; there is much room for variation of actual concentrations (within the specification) of any of the critical contaminants to silicon. Alkali metals seem to be the most difficult to remove; e.g., low sodium "MOS" grade still allows for one part per million of sodium in solution. Sodium, unfortunately, is so common that it is a prime contaminant in SiO_2 films, and causes instabilities and voltage degradation in MOS as well as microwave devices.

The types of analyses performed are also listed on the manufacturer's specification. More common wet chemical techniques such as precipitation, titration, volumetric analysis, visible and ultraviolet spectrophotometry are supplemented by the more sensitive atomic absorption and emission techniques. These techniques are generally considered to be subtrace analytical techniques and are becoming more commonly used in the analytical industry.

Water is a major chemical in the processing of semiconductors. Cleansing and rinsing operations, dilutions of acids, plating bath formulations all involve the use of high purity water. The types of filtrations and chemical reaction necessary to provide water at the highest purity has been mentioned earlier. The selected pretreatment steps are dependent on the types of ionized and nonionized species dissolved within the water. Thus, in water there are five major types of contaminants: (1) dissolved ionizable gases, e.g. ammonia and carbon dioxide; (2) dissolved nonionic gases such as oxygen; (3) organics, which include living organisms, bacteria, algae and viruses, etc.; pyrogens, or dead residue from bacterial growth and synthetics, organic and natural molecules such as hydrocarbons, oils and carbohydrates in general and the decay products of organic materials; (4) particulate matter such as dirt, sand, colloids, etc., (5) ionizable salts such as sodium, calcium, chlorides, sulphates, etc. The water is, therefore, a major source of contamination

TABLE A-7. TYPICAL MANUFACTURERS' ANALYSES

p-TYPE AND n-TYPE DOPANTS

BORON TRIBROMIDE

Boron Tribromide

ULTREX, For Dopant Use, Certificate Provided

Reporting Actual Lot Analysis

BB₃ FW 250.52

Actual Analysis Lot 331383

Non-Metallic Impurities (in ppm)

Arsenic (As) ^a	<0.04
Nitrogen Compounds (as N)	<0.5
Phosphate (PO ₄)	<0.5
Silicon (Si) ^b	0.07
Sulfate (SO ₄) ^c	1

Metallic Impurities (in ppm)

Aluminum (Al)	0.007
Antimony (Sb)	<0.03
Barium (Ba)	<0.5
Bismuth (Bi)	<0.003
Cadmium (Cd)	<0.005
Calcium (Ca)	0.07
Chromium (Cr)	<0.005
Cobalt (Co)	<0.005
Copper (Cu)	0.006
Gallium (Ga)	<0.005
Germanium (Ge)	<0.005
Gold (Au)	<0.035
Iron (Fe)	0.03
Lead (Pb)	0.006
Lithium (Li) ^d	0.1
Magnesium (Mg)	0.007
Manganese (Mn)	0.002
Mercury (Hg)	<0.05
Nickel (Ni)	<0.005
Potassium (K) ^e	0.4
Silver (Ag)	<0.0005
Sodium (Na) ^d	0.6
Strontium (Sr)	<0.05
Tin (Sn)	0.005
Zinc (Zn)	<0.005

^aBy evolution and silver diethyldithiocarbamate photometry^bAverage value for three ampouled samples evaporated residual boron volatilized as methyl borate analyzed spectrographically (DC arc-indium internal standard in graphite matrix against commercial standards); reading of lines in 2650-3875 Å region; key elements found absent are reported as < (less than) the detection limit^cBy turbidimetry in methanol-water^dBy atomic absorption spectrometry

This product is sensitive to heat and light; thus, it is best stored in a refrigerated or cool room (0° C) and protected from light to reduce leaching of elements from the container and discoloration due to liberation of bromine. Packaged under argon.

PHOSPHORUS OXYCHLORIDE

Phosphorus Oxychloride

For Dopant Use, ULTREX, Certificate Provided

Reporting Actual Lot Analysis

POCl₃ FW 153.33

Actual Analysis Lot 407957

Non-Metallic Impurities (in ppm)

Ammonium (NH ₄)	<1
Arsenic (As) ^a	<0.04
Nitrate (NO ₃)	<1
Sulfate (SO ₄) ^b	<1

Metallic Impurities (in ppm)

Aluminum (Al)	0.02
Bismuth (Bi)	<0.01
Cobalt (Co)	<0.02
Copper (Cu)	<0.01
Gallium (Ga)	<0.02
Iron (Fe)	<0.02
Lead (Pb)	<0.02
Lithium (Li) ^d	<0.1
Magnesium (Mg) ^d	<0.1
Manganese (Mn)	0.002
Nickel (Ni)	<0.02
Potassium (K) ^e	0.3
Silver (Ag)	<0.002
Sodium (Na) ^d	<0.1
Titanium (Ti)	<0.02
Zinc (Zn)	0.02

^aBy evolution and silver diethyldithiocarbamate photometry^bBy turbidimetry in methanol-water^cPolysulfide nitrate and silver by 8-quinoline extraction; evaporation of extract; mineralization with nitric acid and DC arc spectroscopy (essentially after N. M. Kuzmin et al., Zh. Anal. Khim. 24: 429-34 (1969) (Russ.); Chem. Abstr. 74: 27136 (1969); indium internal standard in graphite matrix against commercial standards; reading of lines in 2650-3875 Å region; Average of duplicate ampouled samples; elements found at or below a significant blank value are reported as less than one-third of the blank; elements found at or below 4 blank value near the selection limit is reported as less than the detection limit^dBy atomic absorption spectrometry

TABLE A-7. TYPICAL MANUFACTURERS' ANALYSES (Contd)

ACIDS

ACETIC ACID

Low Sodium MOS Grade

Formula: CH_3COOH
Formula Wt.: 60.05

Chemical/Physical Tests	Meets	ACS Specifications
Assay (CH_3COOH)	99.9%	min
Color (APHA)	10	max
Acetic Anhydride ($(\text{CH}_3\text{CO})_2\text{O}$)	0.01%	max
Residue after Evaporation	0.0008%	max
Specific Gravity @ 60°/60°F	1.049-1.052	

TRACE IMPURITIES IN PARTS PER MILLION
(MAXIMUM)

Aluminum (Al)	0.1	ppm
Arsenic & Antimony (as As)	0.005	ppm
Barium (Ba)	1	ppm
Boron (B)	0.05	ppm
Calcium (Ca)	1	ppm
Chloride (Cl)	1	ppm
Copper (Cu)	0.01	ppm
Heavy Metals (as Pb)	0.3	ppm
Iron (Fe)	0.1	ppm
Lithium (Li)	1	ppm
Magnesium (Mg)	1	ppm
Nickel (Ni)	0.1	ppm
Phosphorus (as PO_4)	1	ppm
Potassium (K)	1	ppm
Sodium (Na)	1	ppm
Strontium (Sr)	1	ppm
Sulfate (SO_4)	0.5	ppm

OTHER TESTS

Dilution Test
 Substances Reducing Dichromate
 Substances Reducing KMnO_4 Passes ACS Tests
 Suitability for Nonaqueous Titration

HYDROFLUORIC ACID

Low Sodium MOS Grade

Formula: HF
Formula Wt.: 20.01

Chemical/Physical Tests	Meets	ACS Specifications
Assay (HF) (by acidimetry)	48.75-49.25%	
Color (APHA)	10	max
Fluosilicic Acid (H_2SiF_6)	0.01%	max
Specific Gravity @ 60°/60°F	1.180	

TRACE IMPURITIES IN PARTS PER MILLION
(MAXIMUM)

Aluminum (Al)	0.05	ppm
Arsenic & Antimony (as As)	0.03	ppm
Barium (Ba)	1	ppm
Boron (B)	0.05	ppm
Calcium (Ca)	1	ppm
Chloride (Cl)	5	ppm
Chromium (Cr)	0.01	ppm
Copper (Cu)	0.1	ppm
Gold (Au)	0.05	ppm
Heavy Metals (as Pb)	0.1	ppm
Iron (Fe)	0.5	ppm
Lead (Pb)	0.1	ppm
Lithium (Li)	1	ppm
Magnesium (Mg)	1	ppm
Nickel (Ni)	0.1	ppm
Nitrate (NO_3)	5	ppm
Oxidizable Species (as SO_2)	2	ppm
Phosphate (PO_4)	5	ppm
Potassium (K)	1	ppm
Residue after Ignition	5	ppm
Silver (Ag)	0.1	ppm
Sodium (Na)	1	ppm
Strontium (Sr)	1	ppm
Sulfate (SO_4)	5	ppm

NITRIC ACID

Low Sodium MOS Grade

Formula: HNO_3
Formula Wt.: 63.01

Chemical/Physical Tests	Meets	ACS Specifications
Assay (HNO_3)	70.0-71.0%	
Appearance	passes ACS test	
Color (APHA)	10	max
Specific Gravity @ 60°/60°F	1.421-1.424	
Residue after Ignition	0.0002%	max
Heavy Metals (as Pb)	0.00001%	max

TRACE IMPURITIES IN PARTS PER MILLION
(MAXIMUM)

Aluminum (Al)	0.1	ppm
Arsenic & Antimony (as As)	0.005	ppm
Barium (Ba)	1	ppm
Boron (B)	0.1	ppm
Calcium (Ca)	1	ppm
Chloride (Cl)	0.08	ppm
Chromium (Cr)	0.1	ppm
Copper (Cu)	0.01	ppm
Iron (Fe)	0.1	ppm
Lithium (Li)	1	ppm
Magnesium (Mg)	1	ppm
Nickel (Ni)	0.05	ppm
Phosphorus (as PO_4)	0.2	ppm
Potassium (K)	1	ppm
Sodium (Na)	1	ppm
Strontium (Sr)	1	ppm
Sulfate (SO_4)	0.5	ppm

TABLE A-7. TYPICAL MANUFACTURERS' ANALYSES (Contd)

SOLVENTS

ACETONE

Low Sodium MOS Grade

Formula: $(CH_3)_2CO$

Formula Wt.: 58.08

Chemical/Physical Tests

Assay $(CH_3)_2CO$ (by GC, corrected for H_2O)	99.5%	
Color (APHA)	10	max
Residue after Evaporation	0.0005%	max
Acidity (as CH_3COOH)	0.002%	max
Alkalinity (as NH_3)	0.001%	max
Aldehyde (as $HCHO$)	0.002%	max
Methanol (CH_3OH) (by GC)	0.05%	max
Substances Reducing $KMnO_4$	passes test	
Water (H_2O) (by Karl Fischer titrn.)	0.5%	max
Chloride (Cl)	passes test	
Resistivity (megohm-cm)	7.0	min

TRACE IMPURITIES IN PARTS PER MILLION (MAXIMUM)

Aluminum (Al)	1	ppm
Antimony & Arsenic (as As)	0.01	ppm
Barium (Ba)	1	ppm
Boron (B)	0.2	ppm
Calcium (Ca)	1	ppm
Copper (Cu)	0.01	ppm
Heavy Metals (as Pb)	0.2	ppm
Iron (Fe)	0.05	ppm
Lithium (Li)	1	ppm
Magnesium (Mg)	1	ppm
Nickel (Ni)	0.01	ppm
Phosphorus (as PO_4)	0.1	ppm
Potassium (K)	1	ppm
Sodium (Na)	1	ppm
Strontium (Sr)	1	ppm

TRICHLOROETHYLENE

Low Sodium MOS Grade

Formula: $ClCH_2CCl_2$

Formula Wt.: 131.39

Chemical/Physical Tests

Color (APHA)	10	max
Residue after Evaporation	0.0005%	max
Acidity (as HCl)	0.0005%	max
Alkalinity (as $NaOH$)	0.001%	max
Free Halogens	passes test	
Water (H_2O) (by Karl Fischer titrn.)	0.005%	max
Resistivity (megohm-cm)	0.1×10^6	min

TRACE IMPURITIES IN PARTS PER MILLION (MAXIMUM)

Aluminum (Al)	1	ppm
Arsenic & Antimony (As)	0.1	ppm
Barium (Ba)	1	ppm
Boron (B)	0.05	ppm
Calcium (Ca)	1	ppm
Chloride (Cl)	1	ppm
Copper (Cu)	0.01	ppm
Iron (Fe)	0.1	ppm
Lead (Pb)	0.1	ppm
Lithium (Li)	1	ppm
Magnesium (Mg)	1	ppm
Nickel (Ni)	0.01	ppm
Phosphorus (PO_4)	0.1	ppm
Potassium (K)	1	ppm
Sodium (Na)	1	ppm
Strontium (Sr)	1	ppm
Heavy Metals	0.1	ppm

and must be included in any control system. Listed below are examples of typical selected analyses before and after water purification. These were based on seeking contaminants which "might" be in the purified water system, with no quantitative evidence other than a period of low yields and degraded device parameters during processing. The desire for better control and more quantitative information is always strongest during those "cyclical" events when for some unknown reason, degradation of an electrical parameter is observed. This has been a common and frequently observed occurrence in the semiconductor industry. The reported value of "zero" however should not be construed as being accurate. What is indicated is that the sensitivity of the particular analytical tool did not allow detection at the subtrace levels probably present.

	Raw Water (PPM)	Purified and Polished Water (PPM)
Alkalinity, Bicarbonate	44.0	0
Alkalinity, Carbonate	0	0
Calcium	65.5	0
Chlorine	91.6	-
Dissolved Solids, Total	100.0	0
Iron	0.296	0.003
Magnesium	26.5	-
pH	6.9	6.6
Sodium	69.7	0
Sulfate	22.0	0
Turbidity, Jackson Units	12	0

Likewise, when manufacturers report higher purity levels and propose new categories of chemicals (e.g., MOS, Spectro-Grades) what they are

indicating is that a new analytical technique has moved the detection sensitivity to new levels; they can now look at their process statistically and say, for example, that although they specify sodium at 10 parts per million, that they are now sure analytically that 95 percent of the time, it runs at less than one part per million. Thus, they can lower their specification, probably raise the unit price because of the higher quoted purity and the quality of the material has not changed 95 percent of the time. The occasional 5 or 10 parts per million batch however can now analytically be rejected and recycled for increased purity.

Other facts of semiconductor processing include contamination from airborne particles, particulate matter in gas lines, metallic chips, dust and handling, all of which have been mentioned earlier. Any proposed control system must have as part of its capability the technique for qualitative and quantitative analysis of these species. The process engineer then can make valid judgments about filtration, purification, types of transfer lines and the general environment in which the semiconductor devices are processed.

Finally, in considering the effects of impurities on the semiconductor device performance, it is necessary to know the concentration as well as the type of impurity, to relate this to the device's electrical performance. Furthermore, even though one may know reasonably accurately the type and concentration of an impurity in a reagent used in wafer processing, what has to be determined in any yield correlation is the actual amount of impurity within the semiconductor. It is important to determine, then, the transfer ratio for each impurity. The transfer ratio can be thought to be an equilibrium ratio of concentrations of impurity in the bulk silicon (or on the surface of silicon) to that concentration in the solution. Part of this program therefore will be to establish these coefficients, so as to predict quantitatively the effect of an impurity species introduced at a particular process step.

A. 1. 7 Effects of Contamination on Microwave Semiconductor Devices

As was discussed in subsection A. 1. 5, contamination has several forms. The process-introduced surface contamination could be ionic (as is most often the case) or nonionic. When it is ionic it will most likely be of positive polarity

and therefore it will affect the tuning varactors with n-type epi (which means almost all tuning varactors) by reducing V_B . The reduction comes about as a result of conductivity modulation in the epi. Positive charge will attract electrons to the surface causing an accumulation region there. Hence, the effective resistivity on the surface is reduced, causing a drop in the breakdown voltage capability. Such a drop, as we have stated earlier, will not occur in a PIN diode since V_B is limited by epi thickness. However, an inverse form of PIN will be affected by positive charge to the first order. This form is the NIP structure with the I-region being of π type. The surface charge, attracting electrons, will invert the surface. The inversion layer will immediately exhibit a channel in the I-V characteristics. Consequently, it is quite efficacious to use NIP diodes to detect ionic charge.

A PIN diode is still useful as a tool to detect ionic contamination. In this case, however, the forward resistance-forward current behavior must be observed and analyzed. From the relationship:

$$R_F = \frac{W_I^2}{2\mu I_F}$$

R_F - I_F curve will give us τ . Since contamination will affect lifetime a pseudo-quantitative method is thus provided to "sense" contamination.

When the contamination is nonionic there are other ways the device is affected. The degree and the nature by which the device degrades depend on the quantity and type of contamination. An undesired impurity, when introduced onto the silicon surface at some point along the process, will move into silicon at a later point when high temperature processing occurs. This could be during diffusion, oxidation, metallization or even assembly. These impurities after moving into silicon will act like traps increasing the recombination-generation probability. The net result is a decrease in lifetime. For a tuning varactor the decrease in lifetime will not be easy to measure because, in general, the process does not have an "anneal-slow cool" step to bring the native lifetime up. In the absence of such an anneal step the lifetime even with no contamination is low. It is not expected to go down measurably lower unless a catastrophic contamination occurs.

However, the indirect effect is a degradation in V_B and/or leakage current. For a PIN or NIP, the lifetime will be measurably lowered and so lifetime testing should be an integral part of contamination detection.

Ionic or nonionic contamination will influence the rate and manner of failures in HTRB stressing. As pointed out in subsection A.1.5, observation of channeling will disclose contamination. Also, time variation in leakage current will disclose contamination.

There is another phenomenon which is drastically affected by surface contamination: post tuning drift (PTD). Since the frequency stability of a microwave system is adversely affected, post tuning drift has attracted much attention lately. The motion of surface charges in a tuning varactor causes a change in capacitance - sometimes very minutely - after a step in voltage. Qualitatively, it has been found that two types of such charges may be present. One type has a short time constant and will give rise to an overshoot in the capacitance change (ΔC) at room temperature. The other type has a longer time constant and results in a lagging capacitance response.

Sometimes it may be possible to make these effects partially cancel each other but the apparently positive result is deceptive. The reason is that the two effects have a substantially different temperature dependence and, therefore, compensation is possible at one temperature only. The tuning varactor processing must, as a consequence, aim at eliminating surface contamination even when V_B , I_R and HTRB testing give acceptable results.

In summary, we have at our disposal several electrical measurement methods such as V_B readings, I-V characteristics observations, lifetime measurements and HTRB testing to tell us about the existence and relative degree of extent of contamination acquired during processing. Combined with spectroscopic analysis, all these measurement techniques will provide a powerful tool to identify and take corrective action against contamination.

APPENDIX B

B.1 STATISTICAL METHODOLOGY

B.1.1 Introduction

The methodology utilized in attempting to reduce the scope of the problem relied primarily upon two useful statistical tools: factor analysis and canonical correlation. This appendix provides the reader with an understanding of the theory underlying these methods as well as the complexities of the actual formulae.

B.2 FACTOR ANALYSIS AND CANONICAL CORRELATION

This section presents an overview of the applicability of factor analysis and canonical correlation to this type of project and explores the objectives of each form of analysis.

B.2.1 Factor Analysis

Factor analysis is useful in exploratory data analysis. It has three general objectives: to study the correlations of a large number of variables by clustering the variables into factors, such that variables within each factor are highly correlated; to interpret each factor according to the variables belonging to it; and to summarize many variables by a few factors. The usual factor analysis model expresses each variable as a function of factors common to several variables and a factor unique to the variable:

$$z_j = a_{j1}f_1 + a_{j2}f_2 + \dots + a_{jm}f_m + U_j$$

where

z_j = the j th standardized variable

m = the number of factors common to all the variables

U_j = the factor unique to variable z_j

a_{ji} = factor loadings

f_i = common factors

The number of factors, m , should be small and the contributions of the unique factors should also be small. The individual factor loadings, a_{ji} , for each variable should be either very large or very small so each variable is associated with a minimum number of factors.

To the extent that this factor model is appropriate for your data, the objectives stated above can be achieved. Variables with high loadings on a factor tend to be highly correlated with each other, and variables that do not have the same loading patterns tend to be less highly correlated. Each factor is interpreted according to the magnitudes of the loadings associated with it. The original variables may be replaced by the factors with little loss of information. Each case receives a score of each factor; these factor scores are computed as:

$$f_i = b_{i1}z_1 + b_{i2}z_2 + \dots + b_{ip}z_p$$

where b_{ij} are the factor score coefficients. Factor scores can be used in later analyses, replacing the values of the original variables. Under certain circumstances these few factor scores are freer from measurement error than the original variables, and are therefore more reliable measures. The scores express the degree to which each case possesses the quality or property that the factor describes. The factor scores have mean zero and standard deviation one.

There are four main steps in factor analysis: first, the correlation or covariance matrix is computed; second, the factor loadings are estimated (initial factor extraction); third, the factors are rotated to obtain a simple interpretation (making the loadings for each factor either large or small, not in-between); and fourth, the factor scores are computed.

B.2.2 Canonical Correlation Analysis

Canonical correlating analysis examines the relationships between two sets of variables, and can be viewed as an extension of multiple regression analysis or of multiple correlation. Multiple regression deals with one dependent variable, Y, and p independent variables, X. The regression problem is to find a linear combination of the X variables that has maximum correlation with Y. In canonical correlation there is more than one dependent Y variable -- there is a set of them. The problem is to find a linear combination of the X variables that has maximum correlation with a linear combination of the Y variables. This correlation is called the canonical correlation coefficient. A second pair of linear combinations, with maximum correlation between the linear combinations and zero correlations with the first pair of linear combinations is found. The number of pairs of linear combinations of the X and Y sets is equal to the number of variables in the smaller set (X or Y). The technique can be used to test the independence of two sets of variables, or to predict information about a hard-to-measure set of variables from a set that is easier to measure. It can also be used to relate a combination of outcome measures to a combination of history or baseline measures. The original and canonical variables can be plotted one against the other in scatter plots.

B.3 ALGORITHMS

This section encompasses the algorithms used in developing the applicable BMDP programs.

B.3.1 Method of Provisional Means

Many BMDP programs compute the mean, variance or sum of squares, skewness, kurtosis and covariance. All but the mean require that deviation about the mean be used in the computations. If the data are kept in computer memory it is possible to first compute the mean and then compute each deviation. However, this restricts the number of cases that can be analyzed.

B.3.2 Covariances and Correlations

All BMDP programs that compute the covariance between two variables use only cases for which both variables have acceptable values. Most programs are even more restrictive and use only cases that contain acceptable values for all the variables in the covariance matrix. We now describe how covariances are computed in all programs.

The formula for the covariance between variable i and k is

$$\text{cov}_{ik} = \sum w_j (x_{ij} - \bar{x}_i)(x_{kj} - \bar{x}_k) / [(N-1) \sum w_j / N]$$

where

x_{ij} is the j th observations for variable i

\bar{x}_i and \bar{x}_k are the means of the variables computed from the cases used in the analysis

w_j is the weight of the j th case (1 if no case weights are specified)

N is the number of observations used in the computation with non-zero weight

Then the covariance is computed recursively as

$$d_{ij} = w_j (x_{ij} - \bar{x}_{i(j-1)}) ; d_{kj} = w_j (x_{kj} - \bar{x}_{k(j-1)})$$

$$W_j = W_{j-1} + w_j$$

$$\bar{x}_{ij} = \bar{x}_{i(j-1)} + d_{ij} / W_j ; \bar{x}_{kj} = \bar{x}_{k(j-1)} + d_{kj} / W_j$$

and

$$s_{ikj}^2 = s_{ik(j-1)}^2 + d_{ij} (x_{kj} - \bar{x}_{kj})$$

where

W_j is the sum of the weights for the first j cases

\bar{x}_{ij} is the mean of the first j cases for variable i

S^2_{ikj} is the sum of squares of cross-products for the first j cases

Then the covariance between variables i and k is

$$S^2_{ikN} / [(N-1)W_N/N],$$

the variance of variable i is

$$S^2_{iiN} / [(N-1)W_N/N],$$

and the correlation between variables i and k is

$$S^2_{ikN} / (S^2_{iiN} S^2_{kkN})^{1/2}.$$

Each program description specifies the cases that are used in the computations.

B.3.3 Hotelling's T^2 and Mahalanobis D^2

The pooled within-groups covariance between each pair of variables (say x and y) is computed using only cases for which both x and y are acceptable values; i.e., are not equal to the missing value codes and not out of range.

Let (x_{ij}, y_{ij}) be the values of x and y for the j th case in the i th group.

Then

$$\bar{x}_i = \sum_j x_{ij} / n_i$$

is the mean of x in the i th group where n_i is the number of pairs of acceptable values (x_{ij}, y_{ij}) . When two groups are being compared, the pooled within-groups covariance is c_{xy} computed using data from only the two groups.

$$c_{xy} = \frac{\sum_{i=1}^2 \sum_{j=1}^{n_i} (x_{ij} - \bar{x}_i)(y_{ij} - \bar{y}_i)}{\sum_{i=1}^2 (n_i - 1)}$$

If there is only one group, the summation over i is omitted.

Let $C = (c_{kl})$ be the covariance matrix computed between all pairs of variables in the analysis and $C^{-1} = (c_{kl})^{-1}$ be the inverse of the covariance matrix.

Mahalanobis D^2 is computed only if the sample size n_i in each group is greater than 1. Let \bar{X}_1 represent a column vector of means for the first group and \bar{X}_2 for the second group. Then to compare two groups

$$D^2 = (\bar{X}_1 - \bar{X}_2)' C^{-1} (\bar{X}_1 - \bar{X}_2)$$

where the prime indicates matrix transposition

$$T^2 = D^2 / \left(\frac{1}{h_1} + \frac{1}{h_2} \right)$$

where h_1 and h_2 are the harmonic means of the sample sizes n_1 and n_2 respectively used in computing the covariance for each pair of variables. Then

$$h_1 = \left[\sum_{\text{all pairings}} \frac{1}{n_1} \frac{v(v+1)}{2} \right]^{-1}$$

B.3.4 Bartlett's Statistic

Bartlett's statistic for homogeneity of group variances is computed using only groups having nonzero variances. The formula is

$$M = (N-g) \ln \left[\sum_i (n_i - 1) s_i^2 / (N-g) \right] - \sum_i (n_i - 1) \ln (s_i^2)$$

where

g = the number of groups with nonzero variances

n_i = frequency of the i th group

$$N = \sum n_i$$

$$s_i^2 = \text{variance of group } i$$

The level of significance of Bartlett's statistic is computed by approximating M by an F statistic

$$F = f_2 M / [f_1 (b - M)]$$

where

$$f_1 = g - 1, \quad f_2 = (g + 1) / A^2,$$

$$A = \frac{1}{3(g-1)} \left[\sum \frac{1}{n_i - 1} - \frac{1}{N - g} \right] \text{ and } b = f_2 / (1 - A + 2/f_2).$$

The F statistic is compared with the F distribution with f_1 and f_2 df.

B.3.5 Maximum Likelihood Factor Analysis

The algorithm used for maximum likelihood factor analysis was developed by R.I. Jennrich and P.F. Sampson at the Health Sciences Computing Facility.

Let R be the sample correlation matrix. The normal theory maximum likelihood estimates are computed for the factor loading matrix A and the unique standard deviation matrix (square roots of one minus the communality for each variable) in the factor analytic decomposition

$$\Sigma = A A' + \Psi^2$$

where Σ is the population correlation matrix. (Maximum likelihood factor analysis is scale free so it does not matter whether the correlation or covariance matrix is used.) Here Ψ is diagonal and the loadings A are canonical.

The program uses a Newton-Raphson iteration

$$\Delta \Psi = - (f''_{ij})^{-1} (f'_i)$$

to minimize a function f of Ψ which is a negative slope affine transformation of the conditional maximum of the likelihood for

the sample given ψ (cf. Jennrich and Robinson, 1969; Clarke, 1970; Joreskog and van Thillo, 1971).

In terms of the eigenvalues

$$\gamma_1 \leq \gamma_2 \leq \dots \leq \gamma_p$$

and vectors

$$w_1, \dots, w_p$$

of $\psi R^{-1} \psi$, the function

$$f = \sum_{m=k+1}^p (\log \gamma_m + \gamma_m^{-1} - 1)$$

where k is the number of factors and p the number of variables.

The required derivatives $f'_i = \partial f / \partial \psi_i$ and $f''_{ij} = \partial^2 f / \partial \psi_i \partial \psi_j$ are given by

$$f'_i = \sum_{m=k+1}^p (1 - \gamma_m^{-1}) w_{im}^2$$

and

$$f''_{ij} = \sum_{m=k+1}^p v_{im} v_{jm} \sum_{n=1}^k \frac{\gamma_m + \gamma_n - 2}{\gamma_m - \gamma_n} w_{in} w_{jn} + 1/2 \delta_{ij} \sum_{m=k+1}^p (3\gamma_m^{-1} - 1) v_{im}^2$$

where

$$-v_m = 2\gamma_m^{-1} R^{-1} \psi w_m$$

If, as frequently occurs during the initial steps, (f''_{ij}) is not positive definite, it is replaced by a matrix of approximate second order derivatives.

$$f''_{ij} = \left(\sum_{m=k+1}^p v_{im} v_{jm} \right) \left(\sum_{m=k+1}^p w_{im} w_{jm} \right)$$

If the value of f is not decreased by the step , the step is halved (i.e., $\Delta\psi$ is replaced by $1/2 \Delta\psi$) and halved again until the value of f decreases or ten halvings fail to produce a decrease. Stepping continues until all values of $\Delta\psi_i$ are less than the convergence criterion or the number of steps equals its prescribed maximum.

Using the converged value of ψ , the eigenvalue problem

$$\psi^2 v_m = \gamma_m R^{-1} v_m , m = 1, \dots, p$$

is solved and the estimated columns of are computed using

$$u_m = \rho_m R^{-1/2} v_m , m = 1, \dots, k$$

where $\rho_m = (1 - \gamma_m)^{1/2}$ is the estimated canonical correlation. The advantage of this parameterization is that it converges smoothly even in Heywood cases -- when some of the diagonal components of ψ are zero.

B.3.6 Canonical Analysis

The covariance matrix is computed by the method of provisional means (Appendix B.3.1). If computations with means assumed to be zero are desired, the products of the means are added back into the covariance matrix and means are set to zero.

The covariance matrix is converted to a correlation matrix and all computations are then made in terms of standardized variables (mean zero, standard deviation one).

Denote the correlation matrix by

$$R = \begin{pmatrix} R_{XX} & R_{XY} \\ R_{YX} & R_{YY} \end{pmatrix}$$

where X denotes the smaller of the two sets of variables. R is stored as a triangular matrix (R is symmetric so only the lower half need be used).

The matrix

$$\begin{pmatrix} 0 & R_{XY} \\ R_{YX} & R_{YY} \end{pmatrix}$$

is pivoted on each of the Y variables to obtain.

$$\begin{pmatrix} & -1 & & -1 \\ -R_{XY}R_{YY}R_{YX} & & R_{XY}R_{YY} & \\ & -1 & & -1 \\ R_{YY}R_{YX} & & -R_{YY} & \end{pmatrix}$$

Pivoting is performed in a stepwise manner such that no variable is pivoted whose squared multiple correlation with previously pivoted variables exceeds $1 - \text{TOL}$, where TOL is specified in the CANONICAL paragraph. TOL thus determines the effective rank of the set of Y variables. Rows and columns corresponding to non-pivoted variables are set to zero.

The eigenvalue-eigenvector problem

$$R_{XY}R_{YY}R_{YX}B = R_{XX}B$$

Loadings for X variables on canonical X variables are obtained by multiplying the canonical X variable coefficients by R_{XX}

$$A_{XX} = B_X R_{XX}$$

Loadings for Y variables on canonical Y variables are obtained by multiplying the canonical Y variable coefficients by R_{YY}

$$A_{YY} = B_Y R_{YY}$$

is then solved for the eigenvalues $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_m > 0$ where m is the smaller of the effective ranks of the two sets of variables; the corresponding eigenvectors are B_1, \dots, B_m .

This eigenvector-eigenvalue problem is solved in three stages.

First, the problem is transformed to the problem

$$\begin{matrix} -1/2 & -1 & -1/2 \\ R_{XX}R_{XY}R_{YY}R_{YX}(R_{XX})' & B^* & = \lambda B^* \end{matrix}$$

R_{XX} is obtained by stepwise pivoting in such a way that no variable is pivoted whose squared multiple correlation with previously pivoted variables exceeds $1 - \text{TOL}$. Rows and columns corresponding to nonpivoted variables are set equal to zero.

Next, eigenvalues and eigenvectors are obtained for the transformed problem. Eigenvalues are obtained by tridiagonalization and Reinsch's (1973) TOLRAT version of QR. Eigenvectors are obtained first for the tridiagonalized matrix and then for the original matrix by inverse iteration. The eigenvectors are normalized so that $B_i' B_i = 1$. Lastly, B is obtained as

$$\begin{pmatrix} -1/2 \\ R_{XX} \end{pmatrix} B^* .$$

Canonical correlations are the square roots of the eigenvalues

$$P_i = \sqrt{\lambda_i} \quad i = 1, \dots, m$$

The coefficients for the canonical variables for the set of X variables are the eigenvectors B_i .

$$B_X = (B_1, \dots, B_m)$$

The coefficients for the canonical variables for the set of Y variables are obtained by dividing the eigenvectors by their corresponding canonical correlations and then multiplying by

$$\begin{matrix} -1 \\ R_{YY}R_{YX} \end{matrix}$$

$$B_Y = \begin{matrix} -1 \\ R_{YY}R_{YX} \end{matrix} (B_1 / P_1, \dots, B_m / P_m)$$

Canonical variable scores for each case are obtained by multiplying the standard scores for the original variables by the canonical variable coefficients

$$\begin{pmatrix} v_X \\ v_Y \end{pmatrix} = \begin{pmatrix} B_X \\ B_Y \end{pmatrix} Z$$

where Z denotes the standard scores for the case.

Canonical variable loadings are the correlations of the original variables with the canonical variables. They are also the regression coefficients for predicting the standardized variables from the canonical variables. As such they may be of value in semantically interpreting the canonical variables. These loadings are analogous to unrotated factor loadings.

APPENDIX C

C.1 CORRELATIONS COEFFICIENTS FOR IMPURITIES

Each table in this appendix contains the correlation coefficients for each of the 27 chemical elements monitored at a particular station with each of the electrical tests comprising the final yield as well as with the composite yield itself.

TABLE C-1

STATION WSH01

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.087	.377	-.073	.098	-.102	-.080	-.037	.328	-.068
COPPER	-.130	.198	-.103	-.065	-.134	-.222	-.038	.241	-.034
MAGNESIUM	-.181	.014	.075	-.121	.011	.040	-.083	.156	-.030
CADMIUM	-.184	-.127	-.024	-.362	-.030	-.222	-.075	.090	-.021
BORON	.383	-.021	-.179	.058	-.115	.099	.149	-.149	.015
GERMANIUM	-.044	-.153	-.046	-.169	-.134	-.182	-.027	.163	-.018
PHOSPHOROUS	-.087	-.257	-.073	-.345	-.172	-.411	-.033	.032	.025
CHROMIUM	-.282	-.371	.007	-.398	-.111	-.370	-.067	-.019	.052
IRON	-.164	-.271	.031	-.336	-.150	-.265	-.068	.079	.021
SODIUM	-.050	.242	-.062	-.000	-.093	-.068	-.026	.218	-.042
SILVER	-.149	-.168	-.108	-.340	-.165	-.419	-.032	.047	.022
CALCIUM	-.282	-.242	.113	-.285	.038	-.059	-.090	.004	.020
MERCURY	.160	.006	-.034	-.114	-.127	-.046	-.024	.182	-.055
ALUMINUM	-.317	-.250	-.065	-.271	.365	-.029	-.064	-.317	.014
TIN	-.178	-.268	-.101	-.329	-.127	-.434	-.027	-.048	.048
ARSENIC	-.106	-.213	-.071	-.265	-.158	-.313	-.031	.130	-.003
MOLYBDENUM	-.297	-.285	.026	-.381	-.131	-.323	-.074	.054	.038
CORALT	.098	-.013	-.039	-.130	-.142	-.078	-.027	.210	.051
POTASIUM	.224	.065	-.048	-.133	-.123	-.055	-.023	.118	-.051
GOLD	.171	.012	-.026	-.091	-.119	-.021	-.022	.180	-.052
ZINC	.055	.083	-.105	-.179	-.119	-.158	-.046	.209	-.065
PALLADIUM	.112	-.011	-.094	-.279	-.164	-.265	-.028	.056	-.009
GALLIUM	-.178	-.269	-.105	-.330	-.124	-.435	-.025	-.051	.048
LEAD	.296	-.131	-.216	-.134	-.161	-.093	.130	-.074	-.005
ANTIMONY	-.131	-.153	-.107	-.336	-.175	-.403	-.034	.078	.012
MANGANESE	-.181	-.097	.103	-.167	-.098	-.066	-.080	.176	-.006
NICKEL	-.280	-.353	-.037	-.431	-.081	-.395	-.068	-.039	.043

TABLE C-2

STATION DIP02

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.113	.216	-.086	.025	-.116	-.044	-.046	.156	-.078
COPPER	.117	.101	-.206	.099	.094	.058	-.045	-.017	-.182
MAGNESIUM	.237	.120	-.052	-.099	-.084	-.031	-.009	.050	-.046
CADMIUM	-.261	-.107	.106	-.304	.271	-.016	-.078	-.091	-.015
BORON	.203	-.125	-.136	.037	-.031	.092	-.027	-.256	.025
GERMANIUM	-.219	.077	-.163	-.166	-.185	-.380	-.065	.228	-.055
PHOSPHOROUS	-.438	.221	-.071	.152	.033	-.088	-.079	.228	-.061
CHROMIUM	-.281	-.010	-.148	-.113	-.169	-.373	-.061	.163	-.034
IRON	-.268	.274	-.159	.278	-.080	-.054	-.062	.265	-.111
SODIUM	-.172	.327	-.124	.305	-.075	.033	-.069	.266	-.107
SILVER	-.068	.024	-.166	-.182	-.194	-.338	-.036	.128	-.044
CALCIUM	-.072	.326	-.176	.193	-.164	-.085	.005	.281	-.129
MERCURY	-.202	.313	-.167	.313	-.068	-.002	-.043	.264	-.136
ALUMINUM	-.223	-.099	-.045	-.197	-.184	-.434	-.056	.121	-.077
TIN	-.423	.042	-.113	-.132	-.076	-.352	-.091	.205	-.047
ARSENIC	-.230	.097	-.213	-.096	-.185	-.360	-.046	.223	-.064
MOLYBDENUM	-.204	.182	-.128	-.083	-.134	-.272	-.085	.262	-.083
COBALT	-.057	.106	-.153	-.146	-.184	-.289	-.060	.181	-.058
POTASIUM	-.244	.302	-.118	.331	-.058	.027	-.068	.262	-.098
GOLD	-.215	.249	-.169	.130	-.152	-.165	-.079	.277	-.093
ZINC	.084	.102	-.163	-.012	-.014	-.071	-.086	.060	-.162
PALLADIUM	-.028	.133	-.217	.197	-.079	-.034	-.030	.094	-.147
GALLIUM	-.204	.157	-.169	.111	-.144	-.239	.041	.250	-.152
LEAD	-.372	-.018	-.152	-.206	-.123	-.437	-.073	.201	-.051
ANTIMONY	-.106	.007	-.141	-.265	-.188	-.391	-.053	.156	-.039
MANGANESE	.056	.121	-.102	-.109	-.165	-.200	-.052	.147	-.062
NICKEL	-.278	.086	-.183	-.071	-.159	-.347	-.076	.222	-.065

TABLE C-3

STATION CLE03

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.199	.102	-.353	.138	-.182	-.048	.030	-.040	-.160
COPPER	-.198	-.238	-.032	-.466	-.106	-.570	-.020	.105	-.065
MAGNESIUM	.059	-.026	-.323	-.107	-.187	-.305	.015	.010	-.168
CADMIUM	.144	.016	-.348	.043	-.180	-.128	.019	-.060	-.149
BORON	.006	-.160	-.053	-.135	.312	.123	-.038	-.337	-.053
GERMANIUM	.241	.039	-.209	-.061	-.173	-.079	-.016	.120	-.163
PHOSPHOROUS	-.209	-.266	-.082	-.496	-.077	-.562	-.026	.067	-.089
CHROMIUM	.121	.004	-.323	-.013	-.164	-.178	.017	-.037	-.174
IRON	.097	-.031	-.322	-.061	-.116	-.179	.014	-.058	-.178
SODIUM	-.046	-.090	-.213	-.117	.040	-.067	-.022	-.115	-.158
SILVER	.188	.040	-.306	.029	-.206	-.156	.026	-.029	-.160
CALCIUM	.149	.091	-.352	.108	-.170	-.077	.031	-.040	-.144
MERCURY	.151	-.096	-.300	.018	-.033	.050	-.027	-.195	-.096
ALUMINUM	.199	.070	-.356	.118	-.132	-.025	.022	-.078	-.177
TIN	.173	.123	-.155	-.020	-.174	-.019	-.012	.194	-.117
ARSENIC	.222	.074	-.347	.105	-.171	-.027	.025	-.043	-.139
MOLYBDENUM	.251	-.036	-.129	.054	-.155	-.027	.010	-.097	-.109
COBALT	.200	.102	-.342	.127	-.187	-.045	.026	-.023	-.165
POTASIUM	.129	-.027	-.267	.135	-.186	-.034	.004	-.152	-.047
GOLD	.089	-.031	-.312	-.009	-.146	-.172	-.003	-.098	-.130
ZINC	-.226	-.253	-.040	-.500	-.094	-.596	-.021	.106	-.063
PALLADIUM	.318	-.112	-.212	-.144	-.185	-.187	.027	-.088	-.116
GALLIUM	.255	-.035	-.312	.043	-.039	.025	-.006	-.176	-.153
LEAD	.125	-.009	-.030	-.044	-.104	.006	-.016	.189	-.064
ANTIMONY	-.018	-.208	-.085	-.065	.016	.013	-.040	-.211	.018
MANGANESE	.204	.088	-.334	.122	-.187	-.061	.028	-.039	-.159
NICKEL	-.183	-.231	-.092	-.471	-.124	-.594	-.017	.102	-.087

TABLE C-4

STATION RIN04

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.232	-.015	-.168	.067	.189	.138	.042	-.150	-.096
COPPER	.125	-.140	-.108	-.018	.501	.135	-.036	-.214	-.122
MAGNESIUM	.191	.613	-.141	.407	-.189	.050	.003	.384	.007
CADMIUM	-.151	.631	-.073	.464	.006	.091	-.054	.483	-.121
BORON	.109	-.151	-.070	-.013	.020	.076	-.045	.011	-.087
GERMANIUM	-.023	.059	-.126	-.317	-.167	-.373	-.001	.344	-.120
PHOSPHOROUS	-.147	-.103	-.109	-.203	.130	-.131	-.022	.053	-.157
CHROMIUM	-.071	.471	-.174	.393	.056	.129	.018	.314	-.177
IRON	.037	.333	-.170	.265	.057	.100	-.001	.204	-.137
SODIUM	.320	.060	-.192	.116	-.025	.140	.080	-.103	-.011
SILVER	.072	.614	-.011	.378	-.111	.052	.036	.426	.014
CALCIUM	.054	.371	-.024	.236	-.105	.047	.098	.246	.096
MERCURY	.141	.478	-.206	.405	-.045	.157	.083	.244	-.116
ALUMINUM	.281	-.057	-.185	.075	.158	.227	-.028	-.243	-.028
TIN	-.162	.453	.041	.354	.039	.137	-.064	.487	-.095
ARSENIC	-.148	-.041	.021	-.036	.186	.104	-.022	-.053	-.116
MOLYBDENUM	.191	.449	-.166	.421	-.125	.168	.068	.305	-.065
COBALT	.151	.097	-.048	.127	.228	.180	.046	-.024	-.062
POTASIUM	.280	.032	-.175	.101	.091	.134	.073	-.122	-.088
GOLD	.203	.351	-.110	.256	-.178	.072	.193	.179	.060
ZINC	.140	-.135	-.108	-.011	.481	.128	-.038	-.218	-.111
PALLADIUM	.286	-.104	-.166	-.185	-.159	-.140	.007	-.010	-.076
GALLIUM	.228	.200	-.214	.206	.026	.180	.052	.001	-.077
LEAD	-.127	-.089	-.013	-.190	-.109	-.256	-.031	.299	-.072
ANTIMONY	.091	.282	-.166	.297	-.075	.148	.013	.304	-.119
MANGANESE	.016	.715	-.108	.473	-.080	.097	-.029	.486	-.086
NICKEL	.145	-.132	-.128	.035	.261	.125	-.044	-.240	-.083

TABLE C-5

STATION BDE05

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.035	-.080	-.078	-.304	-.215	-.323	-.040	.152	-.033
COPPER	-.038	.119	-.041	-.112	-.083	-.099	-.016	.147	-.031
MAGNESIUM	.350	-.099	.198	-.066	-.198	-.081	-.035	.010	.093
CADMIUM	-.309	-.271	-.064	-.562	-.075	-.657	-.015	.139	-.041
BORON	.191	-.165	.378	-.079	-.075	-.012	-.013	-.029	.050
GERMANIUM	.179	.085	.016	-.092	-.148	-.062	-.027	.130	-.080
PHOSPHOROUS	.138	-.093	-.037	-.174	-.271	-.360	.179	.056	-.069
CHROMIUM	-.018	-.116	.063	-.267	-.185	-.345	-.034	.062	-.050
IRON	-.177	-.155	.072	-.226	-.113	-.361	-.022	.060	-.067
SODIUM	.139	-.137	-.124	-.108	.311	.037	-.045	-.167	-.132
SILVER	-.017	-.039	.015	-.295	-.179	-.343	-.033	.113	-.058
CALCIUM	.217	-.157	-.007	-.163	-.027	-.086	-.058	-.117	-.099
MERCURY	.019	-.025	-.179	-.011	-.148	-.079	.061	-.059	-.122
ALUMINUM	.113	-.137	-.120	-.244	.076	-.119	-.050	-.042	-.150
TIN	-.002	-.315	-.012	-.407	-.190	-.462	-.063	.031	.025
ARSENIC	-.061	-.171	-.107	-.029	.087	.021	.053	-.260	-.107
MOLYBDENUM	.111	-.205	.230	-.250	-.233	-.270	-.043	.085	-.016
COBALT	.028	-.072	-.079	-.313	-.206	-.320	-.039	.160	-.037
POTASIUM	.017	-.063	-.082	-.337	-.195	-.332	-.037	.185	-.043
GOLD	-.073	-.165	.069	-.313	-.152	-.382	-.002	.037	-.066
ZINC	-.203	-.092	-.033	.020	.007	.062	-.023	-.006	-.068
PALLADIUM	.131	-.145	.047	-.218	-.266	-.296	-.049	.067	.024
GALLIUM	-.084	-.142	-.012	-.292	-.076	-.324	-.045	-.029	-.063
LEAD	.184	-.170	.377	-.092	-.076	-.028	-.013	-.025	.050
ANTIMONY	-.105	-.114	-.030	-.331	-.146	-.386	-.043	.081	-.063
MANGANESE	.136	-.175	.349	-.188	-.128	-.150	-.023	.022	.027
NICKEL	-.036	.114	-.034	-.102	-.089	-.105	-.017	.144	-.027

TABLE C-6

STATION BDI06

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.309	-.271	-.064	-.562	-.075	-.657	-.015	.139	-.041
COPPER	-.309	-.271	-.064	-.562	-.075	-.657	-.015	.139	-.041
MAGNESIUM	-.012	-.221	.027	-.158	-.169	-.211	-.033	.006	.034
CADMIUM	-.309	-.271	-.064	-.562	-.075	-.657	-.015	.139	-.041
BORON	.191	-.165	.378	-.079	-.075	-.012	-.013	-.029	.050
GERMANIUM	.098	.034	-.052	-.167	-.181	-.195	-.033	.070	.015
PHOSPHOROUS	.078	-.044	-.071	-.090	-.330	-.304	-.033	.084	.076
CHROMIUM	.003	-.041	-.041	-.117	-.188	-.181	-.036	.030	.026
IRON	-.081	.011	-.072	-.224	-.129	-.239	-.025	.134	-.012
SODIUM	-.210	-.089	-.043	.017	.011	.057	-.023	-.004	-.070
SILVER	-.013	.120	-.047	-.086	-.092	-.077	-.018	.123	-.013
CALCIUM	-.068	-.141	-.070	-.184	-.174	-.281	-.034	-.039	.053
MERCURY	.090	.200	-.261	.16	.042	.204	.135	-.116	-.050
ALUMINUM	.227	.114	-.136	-.005	-.232	-.040	.113	.067	.118
TIN	.248	-.186	.310	-.127	-.108	-.046	-.031	-.069	.079
ARSENIC	.460	-.215	.175	-.082	-.176	-.027	.019	-.158	.070
MOLYBDENUM	.123	-.064	.006	-.120	-.257	-.208	-.025	.039	.028
COBALT	-.380	-.311	-.054	-.757	-.052	-.943	-.013	.284	-.025
POTASIUM	-.380	-.311	-.054	-.757	-.052	-.943	-.013	.284	-.025
GOLD	.220	.008	-.112	-.072	-.254	-.147	.045	-.015	.099
ZINC	.088	-.239	.353	-.270	-.086	-.252	-.016	.044	.042
PALLADIUM	.129	-.148	.047	-.215	-.266	-.299	-.049	.062	.027
GALLIUM	.068	.040	-.077	-.100	-.206	-.188	.089	.059	-.030
LEAD	.215	-.180	.380	-.085	-.095	-.031	-.017	-.011	.073
ANTIMONY	.181	.076	-.083	-.045	-.239	-.124	.095	.037	.026
MANGANESE	-.045	-.218	.251	-.476	-.133	-.523	-.026	.185	.002
NICKEL	-.152	-.274	-.076	-.396	-.143	-.517	-.028	.003	.064

TABLE C-7

STATION BRE07

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.059	-.036	-.032	-.034	.439	.036	-.011	-.075	-.035
COPPER	-.029	.071	-.012	-.031	-.071	.037	-.011	.116	-.036
MAGNESIUM	.001	-.062	-.035	-.034	-.088	.018	-.011	-.094	-.035
CADMIUM	.002	-.062	-.035	-.034	.588	.019	-.011	-.095	-.035
BORON	.069	-.071	-.034	.003	.563	-.016	-.011	-.090	-.036
GERMANIUM	.046	-.021	-.036	.038	.266	.072	-.012	-.087	-.037
PHOSPHOROUS	.083	-.051	-.036	.001	.367	.039	-.012	-.076	-.038
CHROMIUM	.083	-.071	-.036	.039	.545	.019	-.011	-.104	-.029
IRON	-.028	.066	-.012	-.034	.469	.038	-.012	.112	-.036
SODIUM	.102	-.061	-.057	-.004	.327	.081	-.019	-.136	-.060
SILVER	.017	-.071	-.034	-.033	.516	.019	-.011	-.086	-.035
CALCIUM	.003	-.065	-.037	-.035	.231	.019	-.012	-.098	-.037
MERCURY	.021	-.072	-.036	-.032	.542	.022	-.012	-.087	-.038
ALUMINUM	.069	-.072	-.035	.002	.306	-.017	-.011	-.091	-.036
TIN	.044	-.019	-.033	.039	-.026	.073	-.011	-.085	-.035
ARSENIC	.086	-.055	-.036	.004	.349	.039	-.011	-.085	-.037
MOLYBDENUM	.083	-.071	-.036	.039	.504	.019	-.011	-.104	-.029
COBALT	.083	-.071	-.037	.039	.557	.019	-.011	-.105	-.029
POTASIUM	.102	-.074	-.052	-.006	.537	.047	-.017	-.130	-.051
GOLD	-.027	.066	-.012	-.034	.544	.039	-.012	.112	-.036
ZINC	.016	-.071	-.035	-.034	-.127	.017	-.011	-.084	-.036
PALLADIUM	.298	-.039	-.026	.031	-.074	-.001	-.033	-.045	-.115
GALLIUM	.070	-.071	-.035	.004	.488	-.015	-.011	-.091	-.036
LEAD	.075	-.044	-.051	.038	.509	.093	-.017	-.120	-.055
ANTIMONY	.095	-.062	-.042	-.002	.467	.056	-.013	-.095	-.044
MANGANESE	.053	-.053	-.030	-.034	.506	.090	-.011	-.080	-.035
NICKEL	.000	.000	.000	.000	.000	.000	.000	.000	.000

TABLE C-8

STATION ETC08

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.151	-.631	.054	-.466	-.035	-.098	.072	-.450	.124
COPPER	.167	-.362	-.010	-.275	-.101	-.054	.094	-.266	.352
MAGNESIUM	.103	-.495	-.000	-.366	.004	-.038	.061	-.425	.102
CADMIUM	.121	-.556	.055	-.311	-.106	-.115	.002	-.424	.168
BORON	.091	.009	.024	-.137	-.016	.013	.130	.010	-.007
GERMANIUM	.008	-.180	-.035	-.358	-.106	-.217	.035	-.027	.001
PHOSPHOROUS	-.011	-.268	.197	-.303	-.046	-.085	-.025	-.109	.203
CHROMIUM	.097	-.666	.059	-.519	-.012	-.139	.049	-.453	.103
IRON	.095	-.257	-.011	-.292	-.065	-.068	.113	-.149	.000
SODIUM	-.134	-.120	.241	-.221	.197	.063	.050	-.044	.075
SILVER	.086	-.687	.057	-.513	-.016	-.134	.035	-.469	.120
CALCIUM	.094	-.444	-.036	-.355	-.029	-.107	.089	-.355	.086
MERCURY	.017	-.357	.069	-.359	-.125	-.203	-.014	-.188	.132
ALUMINUM	.065	-.015	.063	-.159	.006	.019	.106	.005	.009
TIN	-.017	-.117	-.032	-.173	-.086	-.044	-.012	-.059	.010
ARSENIC	-.033	-.154	.070	-.252	.119	.032	-.012	-.178	.043
MOLYBDENUM	.104	-.575	.071	-.456	-.028	-.092	.041	-.407	.103
COBALT	.099	-.617	.023	-.430	-.056	-.130	.065	-.444	.119
POTASIUM	.063	-.064	-.104	-.292	-.185	-.346	.176	.122	.133
GOLD	.049	-.603	.198	-.464	-.001	-.128	.009	-.379	.162
ZINC	.255	-.294	-.053	-.237	-.165	-.028	.110	-.245	.246
PALLADIUM	-.006	-.213	-.065	-.138	-.132	-.197	.042	-.114	.050
GALLIUM	.026	-.548	.021	-.520	-.084	-.318	.169	-.252	.080
LEAD	-.069	.060	-.046	-.192	-.088	-.175	-.016	.141	-.032
ANTIMONY	.090	-.077	.085	-.042	-.138	-.065	-.010	-.071	.092
MANGANESE	.115	-.647	.075	-.480	-.005	-.087	.044	-.462	.113
NICKEL	.131	-.625	.066	-.443	-.043	-.117	.077	-.455	.117

TABLE C-9

STATION RIN09

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.118	.685	-.086	.478	.019	.090	-.007	.477	-.134
COPPER	-.031	.614	-.029	.473	-.102	.051	.012	.449	-.116
MAGNESIUM	.099	-.100	-.133	.052	.319	.117	-.057	-.194	-.118
CADMIUM	-.118	.667	-.080	.487	-.007	.086	-.044	.476	-.111
BORON	-.076	-.101	-.148	.117	.026	.087	-.113	-.225	.056
GERMANIUM	-.129	.673	-.082	.446	-.013	.047	-.041	.505	-.117
PHOSPHOROUS	-.118	.674	-.074	.480	-.001	.087	-.042	.486	-.118
CHROMIUM	-.118	.676	-.076	.481	-.001	.085	-.036	.487	-.120
IRON	-.122	.667	-.079	.485	-.009	.080	-.042	.482	-.116
SODIUM	-.106	.581	-.127	.479	.025	.096	-.046	.386	-.142
SILVER	-.132	.670	-.076	.478	.004	.088	-.044	.485	-.122
CALCIUM	-.062	.591	-.115	.463	.078	.134	-.059	.374	-.158
MERCURY	-.119	.673	-.075	.479	-.004	.082	-.038	.487	-.118
ALUMINUM	-.122	.653	-.090	.487	-.014	.073	-.033	.467	-.121
TIN	-.119	.672	-.075	.482	-.004	.084	-.042	.485	-.116
ARSENIC	-.115	.676	-.074	.481	-.004	.086	-.041	.487	-.113
MOLYBDENUM	-.120	.670	-.078	.485	-.007	.082	-.042	.483	-.116
COBALT	-.165	.592	-.119	.394	.132	.112	-.046	.319	-.106
POTASIUM	-.130	.678	-.087	.470	.035	.096	-.019	.466	-.134
GOLD	-.116	.673	-.072	.481	-.004	.085	-.042	.486	-.116
ZINC	-.028	.403	-.159	.280	.016	.138	-.034	.133	.077
PALLADIUM	-.102	.688	-.074	.457	-.032	.041	-.010	.513	-.125
GALLIUM	-.124	.675	-.079	.471	.003	.076	-.028	.489	-.126
LEAD	-.116	.673	-.075	.480	.004	.089	-.043	.483	-.118
ANTIMONY	-.118	.668	-.081	.490	-.008	.087	-.039	.477	-.116
MANGANESE	-.133	.606	-.096	.480	-.015	.071	-.056	.434	-.112
NICKEL	-.129	.662	-.084	.487	.000	.083	-.043	.468	-.118

TABLE C-10

STATION DIP10

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.236	-.161	.197	-.037	.044	.018	-.073	-.010	.115
COPPER	.168	-.124	-.117	-.007	.428	.136	-.042	-.219	-.092
MAGNESIUM	.151	-.130	-.104	-.012	.487	.126	-.039	-.214	-.111
CADMIUM	-.321	-.172	.150	-.209	.373	.112	-.072	-.207	.070
BORON	.278	.409	-.191	.340	-.055	.183	-.039	.212	-.075
GERMANIUM	.151	-.123	-.106	-.013	.493	.128	-.038	-.209	-.114
PHOSPHOROUS	.147	-.125	-.103	-.014	.506	.129	-.037	-.213	-.113
CHROMIUM	.149	-.121	-.112	-.009	.474	.129	-.041	-.205	-.117
IRON	.142	-.125	-.111	-.007	.490	.127	-.040	-.212	-.115
SODIUM	.130	-.139	-.115	-.004	.458	.126	-.043	-.220	-.116
SILVER	.151	-.124	-.107	-.012	.486	.127	-.039	-.209	-.114
CALCIUM	.144	-.128	-.106	-.012	.503	.128	-.038	-.214	-.114
MERCURY	.139	-.125	-.113	-.003	.489	.130	-.042	-.213	-.115
ALUMINUM	.159	-.133	-.095	-.013	.465	.126	-.040	-.213	-.114
TIN	.218	-.083	-.145	.019	.148	.169	-.065	-.200	-.006
ARSENIC	.151	-.106	-.112	.001	.479	.134	-.042	-.197	-.114
MOLYBDENUM	.147	-.108	-.112	.002	.484	.135	-.043	-.199	-.115
COBALT	.141	-.129	-.098	-.020	.527	.131	-.038	-.215	-.112
POTASIUM	.096	-.159	-.067	-.021	.486	.134	-.050	-.216	-.095
GOLD	.106	-.158	-.070	-.044	.590	.141	-.047	-.234	-.099
ZINC	.169	.048	-.112	.082	-.184	.070	-.050	-.019	.198
PALLADIUM	.094	-.159	-.154	.041	.161	.102	-.015	-.215	-.128
GALLIUM	.146	-.127	-.106	-.012	.497	.127	-.038	-.213	-.114
LEAD	.151	-.115	-.115	-.005	.471	.132	-.038	-.201	-.119
ANTIMONY	.155	-.115	-.110	-.011	.470	.130	-.041	-.199	-.118
MANGANESE	.151	-.125	-.110	-.007	.468	.128	-.042	-.208	-.115
NICKEL	.146	-.140	-.119	-.020	.405	.125	-.046	-.207	-.123

TABLE C-11

STATION RIN11

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.035	.142	-.042	.183	-.058	.005	-.016	.020	-.045
COPPER	-.028	.139	-.035	.178	-.057	.090	-.014	.065	.035
MAGNESIUM	-.055	.356	-.021	.293	-.061	.022	-.015	.273	-.036
CADMIUM	-.059	.358	-.019	.294	-.060	.021	-.014	.275	-.036
BORON	.000	.194	-.027	.153	.110	.002	-.014	.113	-.030
GERMANIUM	.018	.089	-.023	.006	.031	.036	-.014	.108	-.035
PHOSPHOROUS	-.088	.138	-.023	.086	-.041	.037	-.015	.141	-.029
CHROMIUM	-.021	.250	-.022	.142	-.060	.020	-.014	.186	-.041
IRON	-.034	.141	-.036	.179	-.058	.090	-.015	.067	.042
SODIUM	-.053	.202	-.051	.165	-.010	.038	-.025	.134	-.065
SILVER	.030	.256	-.022	.150	.100	-.014	-.013	.222	-.038
CALCIUM	-.058	.372	-.021	.302	-.055	.021	-.015	.285	-.038
MERCURY	.028	.270	-.023	.160	.097	-.012	-.014	.232	-.040
ALUMINUM	.001	.193	-.026	.155	.108	.001	-.014	.114	-.029
TIN	.020	.083	-.022	.001	.030	.035	-.014	.103	-.034
ARSENIC	-.087	.135	-.023	.079	-.034	.034	-.015	.141	-.035
MOLYBDENUM	-.023	.250	-.022	.142	-.059	.020	-.014	.186	-.041
COBALT	-.022	.252	-.022	.143	-.060	.020	-.014	.188	-.041
POTASIUM	-.044	.261	-.042	.231	-.067	.013	-.019	.131	-.057
GOLD	-.021	.137	-.037	.177	-.061	.091	-.015	.063	.072
ZINC	.031	.258	-.022	.152	.099	-.014	-.014	.224	-.039
PALLADIUM	-.031	.251	-.005	.178	-.123	.037	-.022	.185	-.052
GALLIUM	-.000	.194	-.027	.152	.110	.001	-.014	.113	-.029
LEAD	.020	.085	-.022	.003	.029	.036	-.014	.106	-.035
ANTIMONY	-.095	.170	-.027	.106	-.044	.041	-.018	.173	-.039
MANGANESE	-.058	.200	-.017	.118	-.057	.036	-.015	.212	-.034
NICKEL	-.058	.200	-.017	.118	-.057	.036	-.015	.213	-.035

TABLE C-12

STATION DSN12

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.012	-.123	-.067	.052	-.051	.005	-.019	-.159	.051
COPPER	-.084	-.224	.172	-.382	-.198	-.403	-.047	.181	-.050
MAGNESIUM	.108	.137	-.053	.159	.068	.137	.076	.144	-.157
CADMIUM	-.020	-.105	-.061	-.097	.057	.037	-.036	.046	-.026
BORON	.151	-.120	-.100	-.007	.475	.128	-.033	-.203	-.113
GERMANIUM	.118	-.162	-.136	-.047	.584	.148	-.047	-.297	-.111
PHOSPHOROUS	.272	.008	-.111	.137	-.114	.035	.084	-.081	-.102
CHROMIUM	.209	-.192	.364	-.090	-.038	.000	-.021	-.077	.058
IRON	-.018	-.166	-.020	-.137	.325	.125	-.070	-.181	-.093
SODIUM	.150	-.121	-.100	-.008	.480	.128	-.034	-.205	-.113
SILVER	-.144	-.217	-.075	-.343	.240	-.140	-.049	-.231	-.030
CALCIUM	.177	-.105	-.101	.009	.404	.129	-.017	-.173	-.117
MERCURY	.037	.282	-.038	.286	-.138	.076	.107	.186	.138
ALUMINUM	.143	-.086	-.102	.028	.421	.146	-.023	-.178	-.109
TIN	.008	-.087	-.081	-.017	.038	.038	-.026	-.204	.064
ARSENIC	.149	-.099	-.014	-.023	.065	.042	-.028	-.153	-.105
MOLYBDENUM	.193	-.189	.377	-.095	-.056	-.009	-.022	-.062	.055
COBALT	.222	-.213	.316	-.094	.019	.041	-.028	-.129	.005
POTASIUM	-.158	-.127	-.107	-.153	.340	.075	-.036	-.279	-.031
GOLD	.003	.092	-.080	-.080	.032	.020	-.030	.022	-.055
ZINC	.070	-.190	.180	-.369	-.247	-.403	-.047	.189	.004
PALLADIUM	.155	-.175	.127	-.218	-.270	-.279	-.049	.050	.020
GALLIUM	.228	.172	-.102	.222	-.252	.041	.128	.054	.157
LEAD	-.038	-.140	-.095	-.108	.019	-.061	-.037	-.192	.044
ANTIMONY	.208	-.200	-.103	-.072	.330	.075	-.033	-.292	-.098
MANGANESE	-.028	-.054	.117	.062	-.070	-.041	-.013	-.034	-.053
NICKEL	-.029	-.094	.114	.020	-.052	-.060	-.023	-.056	-.068

TABLE C-13

STATION NDE13

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.126	-.135	-.108	-.013	.501	.134	-.038	-.213	-.121
COPPER	-.299	-.163	.332	-.175	.220	.098	-.047	-.061	.124
MAGNESIUM	-.226	-.307	.191	-.207	.221	.092	-.088	-.201	.053
CADMIUM	-.029	.358	-.171	.374	-.172	.105	-.083	.219	.080
BORON	.146	-.132	-.104	-.019	.502	.125	-.035	-.215	-.117
GERMANIUM	.068	.074	-.188	.198	.185	.184	-.080	-.064	-.110
PHOSPHOROUS	-.020	-.313	.248	-.219	.189	.154	-.099	-.264	.071
CHROMIUM	-.064	.413	-.145	.377	-.119	.147	-.076	.276	.037
IRON	-.083	.351	-.109	.335	-.084	.163	-.098	.219	.059
SODIUM	.143	-.135	-.099	-.021	.509	.127	-.035	-.217	-.114
SILVER	-.204	.521	-.121	.453	-.050	.114	-.065	.397	-.099
CALCIUM	-.253	-.218	.127	-.056	.200	.167	-.083	-.153	.029
MERCURY	.050	-.094	-.011	-.118	.207	.049	.105	-.128	-.000
ALUMINUM	.156	-.168	-.081	-.061	.490	.107	-.021	-.237	-.118
TIN	.139	-.105	.104	-.195	-.104	-.240	.236	.035	-.065
ARSENIC	.105	-.130	-.045	-.034	.612	.169	.003	-.251	-.118
MOLYBDENUM	-.083	.210	-.230	.168	.162	.179	-.066	.118	-.061
COBALT	.073	.080	-.189	.196	.168	.193	-.080	-.060	-.099
POTASIUM	-.221	.184	-.119	.263	-.086	.094	-.063	.170	-.055
GOLD	-.039	-.246	.047	-.156	.476	.192	-.068	-.277	-.033
ZINC	-.211	-.233	.350	-.258	.108	-.016	-.026	-.067	.117
PALLADIUM	-.218	.282	-.107	.299	-.057	.113	-.056	.240	-.078
GALLIUM	.003	-.175	.178	-.265	.123	-.064	.083	-.105	.030
LEAD	-.123	-.215	-.020	-.027	-.006	.031	-.080	-.182	.157
ANTIMONY	.154	-.076	-.129	.057	.500	.191	-.041	-.214	-.094
MANGANESE	-.045	.150	-.071	.226	.021	.188	-.111	.040	-.016
NICKEL	-.082	.353	-.101	.337	-.097	.171	-.086	.235	.061

TABLE C-14

STATION PHA14

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.062	.236	.023	.050	.029	.047	.067	.173	-.056
COPPER	.073	.140	.057	-.021	.058	.051	.036	.093	-.021
MAGNESIUM	-.095	.042	-.006	-.302	-.032	-.285	.012	.193	-.047
CADMIUM	.018	.205	.047	.012	.070	.052	.055	.151	-.037
BORON	.046	-.051	-.076	-.162	-.183	-.163	-.032	.127	-.009
GERMANIUM	.007	.371	-.011	.285	.090	.214	.104	.198	-.068
PHOSPHOROUS	.207	.041	.057	-.031	-.082	.035	.003	.052	.006
CHROMIUM	-.061	.066	.008	-.252	-.014	-.221	.018	.178	-.043
IRON	.112	.122	.036	-.023	.016	.050	.028	.086	-.014
SODIUM	.073	.140	.057	-.021	.058	.051	.036	.093	-.021
SILVER	.073	.140	.057	-.021	.058	.051	.036	.093	-.021
CALCIUM	-.029	.084	-.025	-.224	-.085	-.219	.019	.216	-.041
MERCURY	.073	.140	.057	-.021	.058	.051	.036	.093	-.021
ALUMINUM	.016	.249	.096	.213	.174	.238	.088	.077	-.041
TIN	.132	.421	-.067	.359	.033	.204	.101	.183	-.068
ARSENIC	.082	.137	.052	-.022	.049	.051	.035	.092	-.020
MOLYBDENUM	.119	.118	.033	-.023	.008	.050	.026	.084	-.012
COBALT	.073	.140	.057	-.021	.058	.051	.036	.093	-.021
POTASIUM	-.005	.471	-.016	.358	-.047	.169	.133	.337	-.045
GOLD	.097	.050	.108	-.054	.113	.052	.013	-.020	-.012
ZINC	-.053	.032	-.020	-.294	-.064	-.272	.006	.185	-.039
PALLADIUM	.070	.127	.043	-.056	.033	.012	.031	.104	-.022
GALLIUM	.099	.007	.066	-.071	.156	.065	-.003	-.093	-.006
LEAD	.041	.422	-.019	.320	-.051	.189	.117	.306	-.047
ANTIMONY	.084	.138	.052	-.023	.046	.051	.034	.097	-.021
MANGANESE	-.099	.039	-.008	-.308	-.035	-.292	.011	.194	-.047
NICKEL	.089	.195	.042	.057	-.030	.089	.032	.164	-.002

TABLE C-15

STATION RIN15

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.114	-.251	-.062	-.343	-.305	-.405	.013	.036	.016
COPPER	-.205	-.130	-.115	-.445	-.115	-.483	-.002	.152	-.059
MAGNESIUM	-.318	-.164	.136	-.364	.253	-.126	-.042	-.077	.095
CADMIUM	-.165	-.227	.211	-.405	.051	-.249	-.071	-.024	.119
BORON	-.116	-.260	.333	-.347	.086	-.176	-.077	-.072	.113
GERMANIUM	-.240	-.041	-.076	-.408	-.104	-.490	-.026	.231	-.068
PHOSPHOROUS	-.244	-.114	.209	-.177	.320	.085	-.045	-.137	.125
CHROMIUM	-.241	-.113	.193	-.176	.322	.086	-.045	-.147	.120
IRON	-.241	-.112	.189	-.176	.322	.086	-.045	-.149	.118
SODIUM	-.066	-.207	-.048	-.443	-.211	-.481	-.016	.113	-.018
SILVER	.225	-.166	.161	-.097	-.239	-.143	-.044	-.004	.082
CALCIUM	-.197	-.209	.288	-.310	.190	-.103	-.064	-.102	.145
MERCURY	-.037	-.164	.034	-.387	-.221	-.451	-.041	.142	.011
ALUMINUM	-.147	-.185	.292	-.195	.232	.041	-.060	-.157	.160
TIN	.220	-.095	-.221	.068	-.120	.092	.104	-.163	.015
ARSENIC	-.114	-.232	-.181	-.404	-.052	-.327	.042	-.042	-.016
MOLYBDENUM	.116	-.212	.217	-.198	-.136	-.148	-.062	-.042	.120
COBALT	-.276	-.131	-.046	-.495	-.067	-.519	-.027	.175	-.033
POTASIUM	-.331	.318	-.022	.076	.257	-.011	-.078	.193	-.066
GOLD	-.104	-.182	.051	-.393	-.137	-.390	-.053	.109	-.032
ZINC	-.329	-.159	.138	-.375	.245	-.149	-.047	-.058	.089
PALLADIUM	-.143	.609	-.069	.338	-.052	-.061	-.051	.508	-.139
GALLIUM	-.069	.628	-.060	.464	-.022	.083	-.040	.441	-.134
LEAD	-.156	-.173	.326	-.169	.251	.056	-.053	-.155	.159
ANTIMONY	-.230	-.097	-.071	-.450	-.107	-.503	-.021	.194	-.048
MANGANESE	-.282	-.153	.161	-.276	.297	-.013	-.039	-.130	.112
NICKEL	-.268	-.124	.184	-.227	.311	.030	-.047	-.127	.114

TABLE C-16

STATION PHD16

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.150	-.043	-.081	-.205	-.349	-.409	.007	.189	-.034
COPPER	-.237	-.050	-.115	-.407	-.090	-.470	.004	.202	-.062
MAGNESIUM	-.204	-.001	-.143	-.342	-.134	-.465	-.000	.240	-.075
CADMIUM	.085	-.168	.073	-.299	-.263	-.367	-.048	.096	.019
BORON	.171	-.175	.253	-.142	-.216	-.238	-.039	.014	.054
GERMANIUM	-.249	-.093	-.053	-.449	-.070	-.465	-.025	.176	-.042
PHOSPHOROUS	-.380	-.311	-.054	-.757	-.052	-.943	-.013	.284	-.025
CHROMIUM	-.380	-.311	-.054	-.757	-.052	-.943	-.013	.284	-.025
IRON	-.380	-.311	-.054	-.757	-.052	-.943	-.013	.284	-.025
SODIUM	-.187	.106	-.022	-.314	-.098	-.432	-.035	.309	-.031
SILVER	.261	-.159	.160	-.080	-.256	-.137	-.047	-.012	.058
CALCIUM	.188	-.166	.114	-.186	-.270	-.247	-.049	.039	.040
MERCURY	.003	-.163	.049	-.366	-.240	-.439	-.044	.132	.002
ALUMINUM	.291	-.157	.204	-.024	-.240	-.084	-.044	-.040	.067
TIN	-.116	.674	-.073	.480	-.002	.085	-.041	.487	-.117
ARSENIC	-.018	-.055	-.171	-.317	-.101	-.326	-.020	.090	-.027
MOLYBDENUM	.245	-.159	.145	-.105	-.261	-.162	-.047	.001	.053
COBALT	-.222	-.086	-.070	-.436	-.107	-.487	-.021	.193	-.048
POTASIUM	.234	-.150	-.228	-.030	-.129	.002	.037	-.177	.020
GOLD	-.228	-.282	.195	-.490	.084	-.287	-.079	-.039	.054
ZINC	-.174	-.080	-.097	-.428	-.123	-.480	.006	.184	-.047
PALLADIUM	-.276	-.153	-.010	-.506	-.045	-.489	-.036	.146	-.028
GALLIUM	-.285	-.181	-.073	-.533	-.097	-.607	-.020	.182	-.049
LEAD	.305	-.150	.215	.002	-.230	-.055	-.042	-.052	.068
ANTIMONY	-.223	-.086	-.070	-.436	-.107	-.487	-.021	.193	-.048
MANGANESE	-.100	.011	-.196	-.295	-.156	-.417	.050	.203	-.077
NICKEL	-.226	-.091	-.070	-.442	-.107	-.495	-.021	.194	-.048

TABLE C-17

STATION ETC17

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.040	.128	.020	.121	-.286	-.192	-.096	.268	-.048
COPPER	-.070	.148	.002	.131	-.276	-.196	-.097	.286	-.057
MAGNESIUM	-.064	.157	.003	.144	-.276	-.183	-.097	.285	-.057
CADMIUM	-.064	.159	.004	.147	-.274	-.182	-.097	.286	-.057
BORON	-.061	.267	.006	.216	-.255	-.105	-.091	.347	-.082
GERMANIUM	-.089	.194	-.019	.199	-.256	-.138	-.097	.296	-.065
PHOSPHOROUS	-.097	.176	-.022	.172	-.261	-.165	-.097	.285	-.062
CHROMIUM	-.065	.160	.002	.148	-.274	-.181	-.097	.287	-.058
IRON	-.074	.156	-.002	.147	-.273	-.183	-.097	.286	-.060
SODIUM	-.025	.162	.022	.119	-.289	-.199	-.094	.297	-.054
SILVER	-.067	.165	.000	.154	-.272	-.178	-.097	.289	-.058
CALCIUM	-.067	.166	-.001	.154	-.273	-.178	-.097	.292	-.060
MERCURY	-.081	.243	-.013	.212	-.254	-.152	-.097	.335	-.070
ALUMINUM	-.069	.134	.001	.128	-.280	-.186	-.097	.276	-.059
TIN	-.142	.573	-.090	.459	-.045	.046	-.059	.429	-.102
ARSENIC	-.128	.444	-.064	.372	-.148	-.049	-.082	.402	-.091
MOLYBDENUM	-.067	.164	.001	.153	-.272	-.178	-.097	.287	-.058
COBALT	-.037	.122	.026	.122	-.287	-.189	-.096	.262	-.047
POTASSIUM	.182	-.131	.169	-.100	-.271	-.192	-.054	.046	.036
GOLD	.010	.084	.057	.087	-.299	-.202	-.093	.236	-.032
ZINC	-.076	.223	-.008	.180	-.265	-.175	-.097	.329	-.068
PALLADIUM	.022	.073	.056	.054	-.302	-.223	-.091	.239	-.030
GALLIUM	-.068	.199	-.002	.182	-.268	-.163	-.097	.317	-.068
LEAD	-.081	.233	-.003	.199	-.255	-.165	-.097	.329	-.067
ANTIMONY	-.109	.397	-.058	.311	-.198	-.097	-.091	.411	-.099
MANGANESE	-.064	.154	.003	.144	-.276	-.182	-.097	.283	-.056
NICKEL	-.069	.185	-.001	.163	-.271	-.177	-.097	.304	-.062

TABLE C-18

STATION RIN18

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.095	-.093	.078	-.034	.023	-.021	-.007	-.088	.167
COPPER	-.124	-.034	.307	-.060	.206	.102	-.062	.026	.204
MAGNESIUM	-.133	-.200	.292	-.231	.300	.111	-.042	-.153	.058
CADMIUM	-.047	-.114	.204	-.131	.030	.039	-.043	.137	.004
BORON	-.243	-.095	.168	-.059	.378	.228	-.135	-.178	.110
GERMANIUM	.181	-.038	.035	.033	-.082	-.053	.007	-.025	.162
PHOSPHOROUS	.188	-.078	.051	.027	-.063	-.036	-.021	-.061	.155
CHROMIUM	.182	-.069	.044	.019	-.051	-.030	-.021	-.061	.171
IRON	.091	-.095	.125	-.039	.009	-.023	-.017	-.054	.185
SODIUM	-.056	-.222	.317	-.222	.216	.057	.007	-.159	.077
SILVER	.174	-.083	.069	.006	-.026	-.016	-.027	-.067	.177
CALCIUM	-.021	-.211	.245	-.188	.186	.044	-.021	-.156	.123
MERCURY	.196	-.061	.061	.029	-.085	-.051	.001	-.039	.161
ALUMINUM	.107	-.111	.087	-.031	.001	-.022	-.035	-.088	.184
TIN	.187	-.037	.032	.034	-.087	-.055	.016	-.022	.159
ARSENIC	.169	-.054	.052	.031	-.081	-.053	-.015	-.033	.167
MOLYBDENUM	.216	-.042	.023	.051	-.076	-.024	-.011	-.047	.161
COBALT	-.141	-.130	.243	-.149	.239	.051	-.048	-.117	.205
POTASIUM	.073	-.103	.092	-.049	.046	-.014	-.009	-.097	.171
GOLD	.169	-.052	.037	.031	-.075	-.048	-.016	-.036	.165
ZINC	-.269	-.157	.281	-.208	.344	.091	-.051	-.122	.145
PALLADIUM	.182	-.189	.213	-.126	-.097	-.094	-.048	-.068	.131
GALLIUM	.168	-.056	.034	.020	-.056	-.042	-.008	-.050	.158
LEAD	.001	-.078	-.009	-.144	.037	-.055	.237	-.035	-.069
ANTIMONY	.169	-.036	.011	.065	-.074	-.031	-.018	-.033	.153
MANGANESE	.236	.117	-.050	.173	-.072	.045	-.050	.024	.157
NICKEL	.121	-.090	.065	-.006	-.031	-.033	-.026	-.067	.169

TABLE C-19

STATION PHS19

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.055	-.244	-.054	-.244	-.169	-.372	-.049	.003	.152
COPPER	-.169	-.220	.035	-.463	-.101	-.582	-.049	.139	-.028
MAGNESIUM	-.097	.364	-.006	.337	.207	.220	-.142	.144	.060
CADMIUM	-.198	-.223	.169	-.234	.271	.096	-.054	-.181	-.002
BORON	-.082	-.286	.165	-.183	.314	.158	-.000	-.218	-.042
GERMANIUM	-.162	-.183	-.064	.020	-.076	-.030	-.047	-.075	.011
PHOSPHOROUS	-.256	-.213	.120	-.202	.278	.087	-.041	-.172	-.014
CHROMIUM	.053	.129	.091	.105	-.007	-.016	-.023	.116	.146
IRON	-.026	-.160	.117	-.168	.062	-.108	-.033	-.081	.170
SODIUM	-.241	-.265	.193	-.337	.241	-.098	-.001	-.146	.134
SILVER	.094	.155	.165	.199	-.060	.034	-.070	.152	.097
CALCIUM	.042	-.027	.095	.041	.060	.040	-.064	-.053	.169
MERCURY	.050	.021	.028	.050	-.036	-.032	-.020	.035	.094
ALUMINUM	.131	-.025	.027	-.003	-.088	-.113	-.019	.020	.157
TIN	.169	-.045	.040	.030	-.075	-.050	-.014	-.029	.168
ARSENIC	.148	-.051	.025	.015	-.096	-.073	.013	-.011	.142
MOLYBDENUM	-.125	.446	-.033	.278	.032	-.024	-.058	.363	-.000
COBALT	.076	-.139	.008	.041	-.113	-.045	-.040	-.071	.141
POTASIUM	-.115	-.238	.043	-.074	-.030	-.088	-.056	-.113	.170
GOLD	.146	-.043	.080	.025	-.046	-.023	-.030	-.030	.074
ZINC	-.409	-.309	.037	-.626	.076	-.569	-.040	.065	.012
PALLADIUM	.051	-.226	-.080	-.239	-.375	-.364	.080	.026	.041
GALLIUM	.114	-.006	.023	-.047	-.127	-.179	-.002	.076	.126
LEAD	-.377	-.305	.311	-.325	.287	-.007	-.054	-.089	.049
ANTIMONY	-.161	.330	-.033	.297	.122	.153	-.092	.210	-.060
MANGANESE	.223	.097	.184	.145	.010	.109	-.093	.015	.169
NICKEL	.017	-.262	.112	-.303	-.125	-.371	-.034	.006	.097

TABLE C-20

STATION ETN20

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.008	-.212	.193	-.163	-.152	-.046	-.039	-.060	.027
COPPER	.173	.071	-.046	-.076	-.176	-.024	-.033	.142	-.021
MAGNESIUM	-.196	-.244	.026	-.087	-.076	-.082	-.050	-.068	-.030
CADMIUM	-.037	-.234	.024	-.225	-.131	-.083	-.086	-.077	.007
BORON	-.081	-.360	.223	-.324	-.000	-.166	-.099	-.162	.055
GERMANIUM	.132	-.066	.103	-.145	-.302	-.116	.005	.162	.005
PHOSPHOROUS	.171	.055	-.037	-.088	-.184	-.039	-.019	.141	-.033
CHROMIUM	.066	-.229	.099	-.250	-.216	-.182	-.034	-.046	.029
IRON	.213	-.118	-.101	-.145	-.209	-.067	.033	.011	-.079
SODIUM	-.261	-.330	.050	-.179	.069	.006	-.080	-.171	-.019
SILVER	.432	-.053	-.130	.073	-.152	.170	.019	-.165	-.043
CALCIUM	-.380	-.311	-.054	-.757	-.052	-.943	-.013	.284	-.025
MERCURY	-.058	-.182	.127	-.175	-.215	-.149	-.110	.045	.032
ALUMINUM	-.071	-.056	-.157	-.220	.073	-.032	-.061	-.041	-.099
TIN	-.130	-.194	.008	-.156	-.117	-.042	-.080	.009	-.051
ARSENIC	-.173	-.181	.000	-.103	-.130	-.054	-.055	.036	-.091
MOLYBDENUM	.086	-.152	-.001	-.197	-.160	-.050	-.090	-.005	.003
COBALT	-.200	-.092	.054	-.101	-.071	-.090	-.070	.103	-.076
POTASIUM	-.218	-.248	-.001	-.078	-.069	-.025	-.042	-.086	-.047
GOLD	.157	-.075	.053	-.121	-.238	-.129	-.053	.067	.027
ZINC	.036	-.026	-.104	-.101	-.092	.020	-.055	.047	-.052
PALLADIUM	.033	-.246	.180	-.241	-.177	-.200	-.051	-.028	.010
GALLIUM	.031	-.208	.186	-.219	-.195	-.189	-.038	.016	.005
LEAD	.100	.010	-.065	-.097	-.113	.007	-.045	.081	-.035
ANTIMONY	.062	-.047	-.027	-.127	-.144	-.022	-.059	.072	-.031
MANGANESE	-.194	-.305	.080	-.142	.028	.049	-.062	-.173	-.024
NICKEL	-.203	-.194	-.119	-.086	.064	.053	-.064	-.111	-.072

TABLE C-21

STATION MES21

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.309	-.057	.126	-.031	-.246	-.050	-.044	.029	.050
COPPER	.273	.114	-.042	-.109	-.084	-.004	-.020	.038	-.046
MAGNESIUM	-.217	-.145	-.054	-.172	.318	.095	-.039	-.273	-.048
CADMIUM	.256	-.238	.113	-.258	-.164	-.230	.028	-.132	.019
BORON	-.210	-.124	-.085	-.166	.298	.077	-.050	-.261	-.029
GERMANIUM	-.043	.215	-.146	.243	-.164	.054	.165	.180	-.108
PHOSPHOROUS	.100	-.239	-.163	-.044	.093	.098	-.048	-.286	-.070
CHROMIUM	-.065	-.249	-.117	-.082	.094	-.040	-.081	-.189	-.039
IRON	-.222	-.142	-.065	-.162	.319	.095	-.038	-.278	-.045
SODIUM	-.244	-.113	-.159	-.136	.277	.058	-.107	-.27	.012
SILVER	.208	-.203	-.047	-.051	.242	.081	.003	-.202	-.105
CALCIUM	-.218	-.149	-.059	-.169	.311	.090	-.015	-.270	-.062
MERCURY	.169	-.182	.261	-.111	-.240	-.203	-.034	.023	.063
ALUMINUM	-.224	-.146	-.056	-.172	.310	.089	-.032	-.260	-.055
TIN	-.002	.151	-.034	-.048	-.075	-.024	-.014	.132	-.026
ARSENIC	-.203	-.221	.047	-.469	-.059	-.512	-.015	.044	.018
MOLYBDENUM	-.297	-.274	-.124	-.542	-.067	-.644	-.002	.088	-.057
COBALT	.033	-.067	-.027	-.020	-.145	.028	.100	-.013	-.115
POTASIUM	-.214	-.140	-.055	-.183	.315	.080	-.040	-.266	-.047
GOLD	.294	.086	-.003	-.095	-.074	.007	-.019	.017	-.043
ZINC	-.098	-.133	-.102	.052	-.089	-.023	.068	-.066	-.055
PALLADIUM	.064	-.189	.176	-.236	-.121	-.135	-.070	-.015	.071
GALLIUM	-.242	-.215	-.078	-.171	.223	.000	-.056	-.252	-.048
LEAD	-.220	-.175	.049	-.225	.335	.094	-.005	-.252	-.029
ANTIMONY	-.116	-.170	-.118	-.286	.048	-.178	-.030	-.200	.034
MANGANESE	-.156	-.247	-.099	-.255	.350	.061	-.059	-.365	-.067
NICKEL	.147	-.100	-.129	.033	.266	.139	-.074	-.198	-.111

TABLE C-22

STATION RIN22

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.081	-.161	.006	-.016	-.162	-.105	-.049	-.099	.065
COPPER	.234	.045	-.084	.036	-.204	.049	-.046	-.015	.228
MAGNESIUM	.003	-.229	-.129	-.137	.428	.188	-.070	-.384	-.082
CADMIUM	.216	-.172	-.168	-.110	-.160	-.154	.150	-.086	-.180
BORON	.148	-.065	-.120	.045	-.200	-.042	-.089	-.073	.066
GERMANIUM	.160	.267	-.091	.175	-.123	-.024	.290	.183	-.119
PHOSPHOROUS	.239	-.020	-.127	.040	-.102	.110	-.050	-.120	.159
CHROMIUM	.247	-.049	-.142	.030	-.058	.134	-.055	-.162	.132
IRON	.267	-.075	-.151	.034	-.065	.134	-.063	-.203	.140
SODIUM	-.180	-.182	-.072	-.180	.346	.126	-.051	-.319	-.066
SILVER	.224	-.158	-.137	-.103	.104	.055	-.046	-.219	.006
CALCIUM	-.103	-.244	-.106	-.094	.065	.024	-.066	-.309	.064
MERCURY	.156	.342	-.069	.198	-.157	-.002	-.052	.242	.008
ALUMINUM	-.196	-.410	-.002	-.181	.208	.171	-.132	-.397	.103
TIN	-.287	-.264	-.110	-.514	.064	-.417	-.049	-.009	-.052
ARSENIC	.199	-.229	.045	-.040	.119	.112	-.075	-.261	-.012
MOLYBDENUM	.212	.322	-.113	.323	-.097	.172	-.051	.139	.059
COBALT	.328	-.070	.193	.039	-.252	-.078	.201	.020	-.023
POTASIUM	.193	-.120	-.126	-.006	.328	.141	-.043	-.222	-.066
GOLD	.220	-.113	-.134	.002	.207	.149	-.049	-.224	-.031
ZINC	.253	-.086	-.159	.036	-.056	.130	-.062	-.196	.118
PALLADIUM	.053	-.182	.071	-.172	-.225	-.233	-.066	-.006	.044
GALLIUM	-.110	-.065	.096	-.172	.198	.069	-.043	-.166	.094
LEAD	.213	-.010	-.121	.025	-.125	.076	-.039	-.089	.175
ANTIMONY	.351	.024	-.175	.041	-.187	.052	.123	-.085	.109
MANGANESE	.239	-.124	-.143	-.062	-.026	.058	-.058	-.165	.062
NICKEL	.251	-.045	-.143	.032	-.056	.131	-.053	-.158	.122

TABLE C-23

STATION CLE23

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.077	-.188	-.123	-.143	.004	-.078	-.085	-.284	.147
COPPER	-.011	-.152	-.162	-.109	.516	.161	-.052	-.375	-.101
MAGNESIUM	-.050	-.175	-.065	.025	-.014	-.007	-.006	-.159	-.005
CADMIUM	-.047	-.113	-.108	-.063	.008	.103	.099	-.076	-.045
BORON	.037	-.030	-.072	.082	.053	.193	.133	-.059	-.042
GERMANIUM	-.211	-.115	.287	-.112	.073	.048	.116	.041	.047
PHOSPHOROUS	-.060	-.176	-.231	-.117	.210	.039	-.076	-.324	.067
CHROMIUM	-.155	-.025	-.068	-.039	.099	.004	-.017	-.030	-.069
IRON	-.296	.385	-.125	.275	.156	.019	.019	.229	-.136
SODIUM	-.057	-.046	-.162	.112	.138	.209	.071	-.158	-.030
SILVER	-.289	-.017	.013	-.083	.432	.123	-.073	-.200	-.000
CALCIUM	-.079	-.068	-.098	.023	.087	-.085	.024	-.165	-.133
MERCURY	-.355	-.016	.022	-.065	.273	.099	-.052	-.033	.025
ALUMINUM	.061	-.060	-.161	.057	.109	.199	.130	-.151	-.028
TIN	.171	-.129	.250	.026	-.129	-.071	-.024	-.051	.106
ARSENIC	.015	-.208	.300	-.153	-.039	.093	-.010	.050	.111
MOLYBDENUM	-.282	-.203	.172	-.104	.129	.133	-.013	-.045	.031
COBALT	.078	-.133	.130	-.008	-.123	-.131	-.026	-.047	.124
POTASIUM	-.135	-.173	-.108	-.289	-.157	-.374	-.030	-.004	.040
GOLD	-.140	-.001	.097	-.060	-.106	-.195	-.036	.179	.125
ZINC	-.146	-.108	-.121	-.145	.347	.081	-.039	-.288	-.011
PALLADIUM	-.181	-.172	-.114	-.231	.283	-.059	-.051	-.278	-.012
GALLIUM	-.199	.315	-.185	.168	.318	.086	-.067	.019	-.054
LEAD	-.365	-.020	.250	-.032	.105	.102	-.053	.141	.013
ANTIMONY	-.250	-.140	.229	-.093	.154	.164	.018	-.012	.075
MANGANESE	.069	-.115	-.049	.003	-.156	-.057	-.053	-.098	-.035
NICKEL	.208	.013	-.210	.038	.078	.165	-.031	-.210	.104

TABLE C-24

STATION RIN24

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.032	-.037	-.029	-.036	.164	-.016	-.014	-.091	-.039
COPPER	.053	-.118	-.058	-.107	.012	.024	.092	-.143	-.029
MAGNESIUM	.053	-.061	-.041	-.070	-.039	-.011	-.015	-.068	-.043
CADMIUM	.053	-.061	-.040	-.070	-.039	-.012	-.015	-.067	-.042
BORON	-.091	-.063	-.021	.019	.115	-.006	-.017	-.121	-.030
GERMANIUM	-.121	-.019	.053	-.032	.512	.042	-.012	-.063	-.039
PHOSPHOROUS	-.200	.120	-.029	-.003	-.018	.043	-.010	-.048	-.043
CHROMIUM	.090	-.057	-.026	-.071	.013	.036	-.013	-.130	.210
IRON	.020	-.096	-.037	-.106	-.013	-.000	.096	-.106	-.012
SODIUM	-.185	.022	-.007	-.043	.400	.032	-.021	-.118	-.069
SILVER	-.077	.049	-.032	-.005	-.058	.101	-.011	-.028	.035
CALCIUM	.050	-.060	-.041	-.066	-.035	-.012	-.012	-.069	-.043
MERCURY	-.078	.044	-.033	-.011	-.052	.104	-.012	-.037	.022
ALUMINUM	-.089	-.057	-.045	.020	.114	-.009	-.014	-.121	-.034
TIN	-.119	-.020	.045	-.033	.511	.045	-.011	-.066	-.037
ARSENIC	-.211	.126	-.017	.001	-.004	.039	-.012	-.036	-.041
MOLYBDENUM	.093	-.057	-.026	-.071	.014	.036	-.012	-.130	.210
COBALT	.085	-.058	-.022	-.073	.012	.036	-.013	-.130	.209
POTASIUM	.015	-.073	-.043	-.079	.170	.014	-.017	-.169	.087
GOLD	.016	-.099	-.037	-.109	-.009	.001	.067	-.109	-.011
ZINC	-.070	.040	-.037	-.008	-.049	.107	-.013	-.040	.030
PALLADIUM	.104	.031	-.034	-.053	.178	-.017	-.029	.015	-.029
GALLIUM	-.090	-.053	-.044	.025	.114	-.011	-.014	-.118	-.034
LEAD	-.120	-.035	.050	-.049	.535	.048	-.013	-.090	-.030
ANTIMONY	-.209	.110	-.029	-.019	.009	.045	-.013	-.057	-.040
MANGANESE	-.058	-.086	-.027	-.113	.216	.040	-.011	-.103	-.035
NICKEL	-.055	-.085	-.029	-.112	.217	.040	-.011	-.103	-.034

TABLE C-25

STATION TH025

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.009	.057	.166	.076	-.120	-.120	.050	.225	-.132
COPPER	-.027	.066	.144	.078	-.109	-.115	.053	.229	-.138
MAGNESIUM	-.029	.059	.143	.077	-.112	-.117	.050	.225	-.136
CADMIUM	-.028	.075	.146	.081	-.103	-.110	.055	.235	-.142
BORON	-.067	-.147	-.049	.008	-.090	-.085	-.036	-.070	.014
GERMANIUM	-.008	.042	.178	.092	-.087	-.083	.049	.191	-.128
PHOSPHOROUS	-.014	-.032	.064	.099	-.105	-.061	.026	.044	-.033
CHROMIUM	-.026	.072	.148	.083	-.103	-.107	.055	.231	-.141
IRON	-.041	.032	.130	.080	-.109	-.111	.043	.195	-.128
SODIUM	-.066	-.136	-.031	.029	-.072	-.063	-.032	-.071	.009
SILVER	-.029	.079	.145	.085	-.097	-.104	.057	.235	-.144
CALCIUM	-.040	.056	.128	.086	-.100	-.105	.050	.214	-.138
MERCURY	-.028	.095	.143	.100	-.072	-.078	.070	.232	-.156
ALUMINUM	-.059	-.123	-.008	.040	-.087	-.076	-.024	-.042	-.002
TIN	-.032	.005	.185	.025	.026	-.012	.071	.129	-.123
ARSENIC	-.028	.058	.153	.073	-.096	-.105	.050	.218	-.136
MOLYBDENUM	-.025	.068	.150	.079	-.104	-.109	.054	.229	-.139
COBALT	-.006	.063	.167	.074	-.120	-.121	.050	.231	-.132
POTASIUM	.208	-.124	.311	.032	-.158	-.075	-.019	-.024	.019
GOLD	-.029	.084	.141	.083	-.096	-.103	.060	.239	-.147
ZINC	-.015	.049	.164	.073	-.117	-.117	.049	.220	-.132
PALLADIUM	.146	-.138	.235	-.046	-.234	-.214	-.016	.079	-.022
GALLIUM	.029	.058	.199	.098	-.105	-.091	.057	.208	-.120
LEAD	-.029	.089	.146	.094	-.079	-.086	.064	.233	-.149
ANTIMONY	.000	.043	.183	.097	-.086	-.079	.059	.189	-.133
MANGANESE	-.026	.070	.148	.078	-.109	-.114	.053	.233	-.139
NICKEL	-.027	.060	.146	.076	-.112	-.118	.050	.226	-.136

TABLE C-26

STATION NIR26

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.055	.280	-.239	.231	.299	.179	.104	.024	-.244
COPPER	-.119	.578	-.147	.425	.089	.126	.007	.370	-.189
MAGNESIUM	-.013	.218	-.239	.193	.345	.186	.091	-.038	-.242
CADMIUM	-.049	.284	-.239	.231	.301	.178	.105	.023	-.244
BORON	.091	.233	-.204	.160	.184	.098	.223	.006	-.202
GERMANIUM	-.071	.267	-.234	.225	.311	.186	.064	.020	-.242
PHOSPHOROUS	.006	.141	-.185	.113	.136	.091	.165	.006	-.200
CHROMIUM	-.047	.265	-.236	.218	.278	.169	.115	.022	-.243
IRON	-.020	.214	-.219	.172	.215	.135	.147	.014	-.228
SODIUM	-.072	.241	-.232	.164	.380	.179	.058	-.066	-.204
SILVER	-.052	.294	-.239	.239	.296	.178	.104	.033	-.244
CALCIUM	-.065	.257	-.240	.203	.325	.179	.096	-.011	-.235
MERCURY	-.044	.287	-.239	.237	.309	.183	.094	.025	-.246
ALUMINUM	-.056	.197	-.240	.154	.374	.184	.073	-.081	-.222
TIN	-.053	.281	-.240	.229	.304	.179	.104	.019	-.243
ARSENIC	-.048	.285	-.239	.232	.298	.178	.107	.025	-.244
MOLYBDENUM	-.050	.284	-.239	.232	.300	.178	.105	.024	-.244
COBALT	-.053	.278	-.239	.227	.301	.178	.104	.020	-.243
POTASIUM	-.110	.398	-.150	.369	.153	.179	-.055	.236	-.203
GOLD	-.053	.278	-.240	.225	.307	.179	.103	.015	-.242
ZINC	-.052	.155	-.189	.137	.176	.122	.091	.014	-.207
PALLADIUM	-.177	.154	-.168	.193	.228	.158	.024	.051	-.196
GALLIUM	-.029	.300	-.236	.254	.323	.192	.075	.033	-.247
LEAD	-.064	.255	-.239	.204	.312	.176	.097	-.003	-.237
ANTIMONY	-.093	.206	-.234	.165	.326	.174	.082	-.041	-.225
MANGANESE	-.050	.283	-.239	.231	.300	.178	.105	.024	-.244
NICKEL	.064	.065	-.207	.106	.399	.175	.054	-.127	-.217

TABLE C-27

STATION WSH27

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.100	-.244	-.391	-.460	.395	-.381	.203	-.032	-.353
COPPER	-.106	-.249	-.393	-.463	.399	-.385	.200	-.031	-.353
MAGNESIUM	-.067	-.221	-.382	-.441	.374	-.361	.220	-.037	-.353
CADMIUM	-.030	-.193	-.370	-.418	.350	-.337	.238	-.043	-.352
BORON	.561	.297	-.077	.053	-.132	.133	.457	-.127	-.233
GERMANIUM	-.099	-.244	-.391	-.459	.394	-.380	.204	-.032	-.353
PHOSPHOROUS	.028	-.149	-.350	-.382	.310	-.298	.266	-.053	-.349
CHROMIUM	.548	.285	-.086	.040	-.119	.121	.454	-.126	-.238
IRON	.407	.159	-.176	-.094	.014	-.009	.415	-.108	-.285
SODIUM	.096	-.097	-.325	-.337	.263	-.252	.297	-.063	-.343
SILVER	-.075	-.227	-.384	-.446	.380	-.366	.216	-.036	-.353
CALCIUM	.229	.010	-.268	-.241	.162	-.154	.352	-.084	-.325
MERCURY	.573	.308	-.068	.066	-.145	.146	.459	-.129	-.227
ALUMINUM	.087	-.104	-.328	-.343	.270	-.258	.292	-.062	-.344
TIN	-.110	-.252	-.394	-.466	.402	-.388	.198	-.030	-.353
ARSENIC	-.062	-.216	-.380	-.438	.371	-.357	.223	-.038	-.353
MOLYBDENUM	-.041	-.201	-.373	-.426	.357	-.344	.233	-.041	-.352
COBALT	-.096	-.242	-.390	-.458	.392	-.379	.205	-.032	-.353
POTASium	-.065	-.219	-.381	-.440	.373	-.359	.221	-.037	-.353
GOLD	.404	.156	-.177	-.097	.016	-.011	.415	-.108	-.286
ZINC	.397	.150	-.182	-.103	.023	-.018	.412	-.107	-.288
PALLADIUM	-.217	-.329	-.422	-.523	.466	-.451	.141	-.011	-.350
GALLIUM	-.097	-.242	-.390	-.458	.393	-.379	.205	-.032	-.353
LEAD	-.054	-.211	-.377	-.433	.366	-.352	.226	-.039	-.353
ANTIMONY	.482	.224	-.131	-.026	-.054	.058	.437	-.118	-.262
MANGANESE	-.085	-.234	-.387	-.452	.386	-.372	.211	-.034	-.353
NICKEL	.016	-.158	-.354	-.390	.319	-.307	.260	-.051	-.349

TABLE C-28

STATION RIN28

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.250	-.191	.021	-.070	-.031	-.015	-.048	-.027	-.039
COPPER	.030	-.172	-.108	.026	-.055	.012	-.060	-.171	.058
MAGNESIUM	.166	.043	-.053	-.233	-.093	-.176	-.016	.077	-.050
CADMIUM	-.299	-.166	.240	-.245	.382	.097	-.056	-.165	.083
BORON	-.096	.681	-.120	.479	.019	.090	.066	.461	-.162
GERMANIUM	-.398	-.241	.053	-.126	.331	.108	-.068	-.194	-.004
PHOSPHOROUS	-.117	.674	-.072	.479	-.001	.086	-.041	.487	-.117
CHROMIUM	-.289	-.015	.327	.004	.088	.056	-.068	.111	.092
IRON	-.317	-.060	.207	-.023	.043	-.024	-.066	.092	.070
SODIUM	-.281	-.122	.077	-.027	.089	.084	-.032	.004	-.029
SILVER	-.263	-.146	.393	-.192	.185	.058	-.038	.007	.126
CALCIUM	-.318	-.206	.338	-.283	.218	-.035	-.073	-.039	.103
MERCURY	-.275	.351	.235	.257	.041	.065	.003	.369	.003
ALUMINUM	.131	.405	-.047	.370	.069	.161	-.081	.194	-.115
TIN	-.249	-.121	.383	-.157	.149	.066	-.026	.031	.121
ARSENIC	-.331	.047	.303	.010	.158	.079	-.065	.130	.085
MOLYBDENUM	-.311	-.128	.318	-.134	.192	.073	-.030	-.010	.098
COBALT	-.262	-.248	.195	-.416	.257	-.122	-.071	-.115	.080
POTASIUM	-.268	-.119	.052	-.018	.072	.078	-.031	-.000	-.039
GOLD	-.211	.052	.290	-.180	.066	-.093	.059	.215	.034
ZINC	.021	-.162	-.110	.029	-.062	.001	-.056	-.158	.050
PALLADIUM	-.198	-.198	-.086	-.193	-.170	-.194	-.052	.031	-.068
GALLIUM	-.180	.266	.164	.220	-.011	.033	.087	.284	-.015
LEAD	-.225	-.180	.303	-.086	.029	.020	-.049	.013	.098
ANTIMONY	-.320	.021	.042	-.063	.405	.107	-.022	-.124	-.005
MANGANESE	-.270	-.129	.370	-.173	.195	.076	-.036	.004	.121
NICKEL	.187	-.032	-.062	-.123	-.005	-.005	-.036	-.161	.019

TABLE C-29

STATION WXE29

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.250	.116	-.043	-.091	-.057	.005	-.014	.027	-.04
COPPER	.255	.119	-.039	-.086	-.071	.002	-.013	.038	-.040
MAGNESIUM	.264	.115	-.033	-.086	-.079	.003	-.012	.038	-.038
CADMIUM	.284	.099	-.023	-.090	-.084	.017	-.003	.024	-.02
BORON	.037	-.054	-.022	-.082	-.069	-.014	-.013	.016	-.04
GERMANIUM	.017	.601	-.115	.478	.028	.180	.057	.377	-.117
PHOSPHOROUS	.257	.120	-.037	-.084	-.075	.001	-.012	.041	-.04
CHROMIUM	.267	.113	-.028	-.085	-.086	.001	-.013	.040	-.03
IRON	.262	.119	-.033	-.085	-.084	-.001	-.014	.044	-.040
SODIUM	.242	.114	-.049	-.098	-.040	.009	-.016	.015	-.04
SILVER	.256	.120	-.038	-.084	-.074	.001	-.013	.040	-.04
CALCIUM	.280	.105	-.020	-.087	-.094	.006	-.010	.036	-.03
MERCURY	.257	.120	-.037	-.084	-.075	.001	-.012	.041	-.040
ALUMINUM	.220	-.032	.044	-.069	-.124	.111	.072	-.028	.07
TIN	.231	-.103	-.055	-.013	.069	.145	.121	-.157	-.03
ARSENIC	.256	.120	-.038	-.086	-.075	-.001	-.012	.042	-.040
MOLYBDENUM	.268	.113	-.029	-.085	-.086	.001	-.013	.040	-.04
COBALT	-.331	-.346	.201	-.557	-.079	-.537	-.047	.129	.02
POTASIUM	.236	.108	-.052	-.102	-.025	.012	-.017	.002	-.04
GOLD	-.108	.677	-.064	.489	.003	.110	-.029	.489	-.104
ZINC	.258	.118	-.038	-.086	-.071	.004	-.011	.037	-.03
PALLADIUM	-.108	.641	-.060	.429	-.039	.035	-.053	.494	-.12
GALLIUM	.149	.059	-.040	-.217	-.035	-.110	.021	.086	-.030
LEAD	.023	-.158	.026	-.069	-.095	.001	.011	-.033	-.01
ANTIMONY	.256	.120	-.038	-.086	-.075	-.001	-.012	.042	-.04
MANGANESE	.261	.116	-.033	-.085	-.078	.001	-.014	.039	-.040
NICKEL	.271	.117	-.031	-.087	-.090	.004	-.011	.042	-.037

TABLE C-30

STATION THE30

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.096	.672	-.086	.458	-.015	.070	-.045	.476	-.114
COPPER	-.221	.298	.251	.160	.149	.103	-.067	.266	.019
MAGNESIUM	-.219	-.269	-.045	-.356	.219	-.222	-.055	-.212	-.058
CADMIUM	-.053	.006	.250	-.087	-.002	-.018	.201	.112	.005
BORON	.042	-.397	.272	-.172	.086	.106	.137	-.346	.131
GERMANIUM	-.097	-.035	.087	-.126	.285	.143	.157	-.125	.004
PHOSPHOROUS	-.016	-.070	.187	-.174	.131	.048	.192	-.044	-.008
CHROMIUM	-.114	-.133	-.077	-.144	.334	.058	-.044	-.311	-.026
IRON	-.140	-.138	-.072	-.160	.371	.073	-.032	-.319	-.024
SODIUM	.079	-.430	.310	-.115	-.075	.026	.089	-.295	.143
SILVER	.044	-.165	-.100	-.086	.014	-.049	-.061	-.253	.001
CALCIUM	-.103	.133	-.045	.042	.072	-.114	-.090	.018	-.061
MERCURY	-.015	.002	.213	-.095	.018	.021	.200	.074	.004
ALUMINUM	-.080	.035	.335	.173	.059	.117	.106	-.002	.042
TIN	.055	-.054	.133	-.072	.036	.108	.166	-.021	.031
ARSENIC	.084	-.055	.084	-.042	.047	.148	.141	-.051	.033
MOLYBDENUM	.043	-.085	.147	-.084	.078	.124	.174	-.066	.036
COBALT	-.081	-.046	.027	-.203	.329	.085	.081	-.199	-.011
POTASium	.189	.063	-.050	-.197	-.089	-.133	-.015	.069	-.048
GOLD	.144	-.128	.049	-.077	.247	.121	.088	-.181	-.104
ZINC	-.242	-.114	.375	-.158	.147	.063	-.009	.034	.116
PALLADIUM	.195	-.072	.014	-.238	-.177	-.205	-.032	.086	-.043
GALLIUM	.146	-.159	-.008	-.012	-.188	-.080	-.047	-.153	.029
LEAD	-.054	-.024	.239	-.102	.050	.034	.179	.061	.022
ANTIMONY	-.049	-.076	.209	-.141	.132	.058	.194	-.044	.006
MANGANESE	-.151	-.147	-.062	-.160	.356	.047	-.032	-.318	-.025
NICKEL	-.276	-.227	.326	-.182	.205	.052	-.024	-.111	.112

TABLE C-31

STATION RIN31

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.055	-.300	-.145	-.257	.434	.052	-.040	-.395	-.071
COPPER	-.086	-.086	-.058	.060	-.056	-.043	-.041	-.052	.013
MAGNESIUM	.109	-.038	-.066	-.067	-.102	-.067	-.038	-.037	-.013
CADMIUM	.143	-.158	.064	-.061	.046	.148	.074	-.146	.071
BORON	-.199	.125	-.149	.072	.329	.092	-.067	-.116	-.071
GERMANIUM	.133	-.155	-.011	-.012	.015	-.012	-.029	-.166	.153
PHOSPHOROUS	-.067	-.146	-.040	.020	-.066	-.053	-.032	-.091	.047
CHROMIUM	.118	-.167	.044	-.041	.133	.173	.060	-.186	-.006
IRON	.112	-.165	.059	-.087	.107	.155	.054	-.149	-.001
SODIUM	.109	.019	.028	-.043	-.094	-.012	.001	.010	-.006
SILVER	-.059	.022	.089	.118	-.138	.097	.100	.075	.111
CALCIUM	.247	-.040	.032	-.212	-.066	-.010	.022	-.015	-.041
MERCURY	.078	-.100	.018	.006	.089	.173	.051	-.108	-.006
ALUMINUM	.098	-.247	.165	.034	-.230	-.058	-.045	-.139	.087
TIN	.142	-.073	.100	.008	-.098	.006	.026	-.026	.221
ARSENIC	.193	-.066	.038	.016	-.062	-.028	-.002	-.052	.163
MOLYBDENUM	.189	-.081	.031	.023	-.062	-.027	-.002	-.069	.168
COBALT	.009	-.155	-.034	.004	-.067	-.007	-.012	-.152	.08
POTASIUM	-.115	-.241	-.060	-.181	.380	.126	-.027	-.400	-.021
GOLD	-.106	-.253	.040	-.176	-.217	-.175	.070	-.032	.119
ZINC	-.082	-.178	-.040	.023	-.070	-.049	-.041	-.125	.04
PALLADIUM	.069	-.276	-.070	-.339	.247	-.127	-.073	-.242	-.13
GALLIUM	.107	-.052	.101	.128	.067	.160	-.006	-.080	-.091
LEAD	.183	-.234	-.002	.015	-.029	.049	.004	-.219	.141
ANTIMONY	.112	-.235	.038	-.043	-.031	-.010	-.024	-.168	.13
MANGANESE	-.062	-.057	.163	-.059	-.055	.082	.114	.031	.131
NICKEL	-.246	-.122	.372	-.156	.143	.068	-.021	.026	.125

TABLE C-32

STATION WXU32

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.250	.116	-.043	-.091	-.057	.005	-.014	.027	-.041
COPPER	.258	.118	-.036	-.085	-.073	.001	-.013	.037	-.040
MAGNESIUM	.259	.119	-.038	-.087	-.074	.005	-.011	.040	-.040
CADMIUM	.270	.109	-.036	-.092	-.073	.021	-.001	.031	-.036
BORON	.229	.076	-.039	-.102	-.087	-.005	-.015	.035	-.049
GERMANIUM	.004	-.331	.128	-.023	-.050	.036	.019	-.232	.075
PHOSPHOROUS	.257	.120	-.037	-.084	-.075	.001	-.012	.041	-.040
CHROMIUM	.260	.120	-.039	-.086	-.079	.003	-.012	.044	-.040
IRON	.258	.121	-.039	-.085	-.077	.001	-.013	.044	-.040
SODIUM	.258	.101	-.028	-.093	-.055	.003	-.018	.010	-.037
SILVER	.256	.120	-.038	-.084	-.074	.001	-.013	.041	-.040
CALCIUM	.267	.117	-.038	-.088	-.081	.010	-.008	.042	-.038
MERCURY	.271	.109	-.023	-.082	-.086	-.003	-.015	.033	-.034
ALUMINUM	.263	.008	.004	-.094	-.045	.128	.074	-.041	.008
TIN	.000	-.094	.208	-.109	.076	.126	.113	-.034	.063
ARSENIC	.256	.120	-.038	-.086	-.075	-.001	-.012	.042	-.040
MOLYBDENUM	.259	.120	-.037	-.086	-.079	.003	-.012	.045	-.040
COBALT	-.021	-.139	-.145	-.351	-.232	-.417	.022	.104	.106
POTASIUM	.236	.107	-.052	-.103	-.025	.013	-.017	.004	-.043
GOLD	.062	-.258	.076	.031	-.155	-.075	-.042	-.169	.072
ZINC	.257	.118	-.038	-.086	-.071	.004	-.011	.037	-.040
PALLADIUM	.047	-.251	.073	-.016	-.176	-.126	-.059	-.138	.059
GALLIUM	.229	-.123	.009	-.266	-.074	-.065	.061	-.079	.007
LEAD	.169	-.220	.199	.006	-.189	-.055	-.025	-.117	.063
ANTIMONY	.210	-.121	.145	.033	-.182	-.060	-.033	-.109	.037
MANGANESE	.257	.120	-.039	-.086	-.074	.002	-.013	.041	-.040
NICKEL	.263	.118	-.037	-.087	-.078	.007	-.009	.041	-.038

TABLE C-33

STATION RIN33

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.069	-.142	-.067	-.035	-.077	-.104	-.040	-.071	.011
COPPER	-.052	-.142	-.067	.025	-.062	-.044	-.019	-.101	.018
MAGNESIUM	-.181	.524	-.118	.281	-.074	-.139	-.057	.462	-.106
CADMIUM	.165	-.205	.144	-.011	-.186	-.070	-.031	-.159	.051
BORON	-.142	-.211	-.111	-.338	-.004	-.319	-.045	-.066	-.023
GERMANIUM	.018	-.150	.004	-.097	.219	.202	.108	-.232	.040
PHOSPHOROUS	-.081	-.061	-.068	.081	-.060	-.036	-.035	-.038	.001
CHROMIUM	-.178	-.200	-.104	-.559	-.003	-.540	-.029	.057	-.051
IRON	-.343	-.281	-.126	-.528	.184	-.461	-.036	-.091	-.042
SODIUM	-.122	.549	-.110	.439	-.058	.038	-.057	.382	-.071
SILVER	-.122	.671	-.073	.471	-.002	.074	-.041	.490	-.111
CALCIUM	-.051	.636	-.106	.451	-.072	.070	-.051	.421	-.087
MERCURY	-.036	.146	-.110	.203	.009	.043	-.048	-.031	-.007
ALUMINUM	-.092	.022	-.089	-.375	-.106	-.479	-.029	.240	-.081
TIN	.086	-.110	.053	-.036	.029	.157	.116	-.102	.049
ARSENIC	.043	-.175	-.011	-.076	.040	.148	.093	-.187	.056
MOLYBDENUM	.100	-.119	.060	-.035	.023	.159	.117	-.112	.051
COBALT	.158	-.078	-.077	-.000	-.024	.120	.143	-.105	.001
POTASIUM	-.104	.047	-.076	.153	-.058	-.028	-.048	.042	-.011
GOLD	-.269	-.233	-.053	-.561	-.095	-.593	.037	.157	-.041
ZINC	-.054	-.119	-.073	-.475	-.107	-.488	-.020	.131	-.058
PALLADIUM	-.229	-.161	-.093	-.444	-.132	-.604	-.042	.182	-.055
GALLIUM	-.099	.656	-.088	.383	-.030	.000	-.045	.506	-.129
LEAD	.303	-.193	.206	-.004	-.159	.074	.088	-.112	.091
ANTIMONY	.093	-.106	.044	-.030	.021	.155	.123	-.105	.041
MANGANESE	-.290	-.178	-.076	-.517	-.085	-.645	-.021	.199	-.059
NICKEL	-.331	.196	-.104	-.189	-.065	-.496	-.040	.417	-.108

TABLE C-34

STATION CLE34

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.045	.517	-.063	.327	-.158	-.007	.074	.545	-.163
COPPER	-.051	-.181	.260	-.149	.119	.137	-.034	-.101	.122
MAGNESIUM	.164	-.032	-.041	-.132	-.241	-.105	-.035	.116	.021
CADMIUM	-.237	-.140	-.199	-.286	.009	-.360	.149	.002	-.113
BORON	.077	-.048	-.143	-.103	.095	.003	.170	-.028	-.094
GERMANIUM	-.004	-.134	-.140	.028	.074	.140	.008	-.134	-.095
PHOSPHOROUS	.159	-.242	.034	-.043	-.138	-.034	.035	-.143	-.024
CHROMIUM	.059	-.055	-.054	.031	-.078	.014	-.015	-.121	.074
IRON	.207	-.128	-.113	.016	-.049	.168	-.022	-.194	.080
SODIUM	.067	-.048	.081	.015	.047	.180	-.107	-.090	.183
SILVER	-.073	-.073	-.122	-.132	.339	.072	.019	-.287	-.038
CALCIUM	.115	-.084	-.008	-.156	-.236	-.174	-.044	.071	.021
MERCURY	.029	-.138	-.149	.017	.073	.121	.028	-.152	-.103
ALUMINUM	.084	-.145	.018	-.038	.034	.184	-.079	-.164	.144
TIN	-.003	-.140	-.117	.021	.108	.158	-.012	-.148	-.070
ARSENIC	-.039	-.149	-.063	-.022	.167	.170	.021	-.148	-.068
MOLYBDENUM	-.012	-.155	-.117	-.037	.015	.068	.028	-.106	-.081
COBALT	.058	-.017	-.089	.009	-.146	-.026	-.016	-.081	.064
POTASIUM	.251	-.019	.100	.004	-.192	-.041	.153	.145	-.097
GOLD	.068	-.160	-.113	-.127	.052	.013	.125	-.185	-.115
ZINC	.060	-.098	-.055	-.073	-.084	-.031	-.045	-.026	.044
PALLADIUM	.165	.012	-.060	-.085	-.218	-.211	.281	.118	-.091
GALLIUM	.009	-.051	-.121	-.092	.264	.044	.121	-.255	-.055
LEAD	-.086	-.148	-.112	.013	.165	.135	-.046	-.136	-.099
ANTIMONY	-.039	-.155	-.156	-.035	.081	.065	-.015	-.119	-.095
MANGANESE	.286	-.142	-.097	-.133	-.100	.033	-.054	-.200	.049
NICKEL	-.082	.617	-.087	.481	-.081	.060	-.058	.441	-.078

TABLE C-35

STATION RIN35

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.002	-.022	.060	-.011	-.033	-.114	-.047	-.004	-.056
COPPER	-.143	.675	-.102	.469	.062	.122	-.069	.428	-.092
MAGNESIUM	-.114	-.095	-.095	-.144	.347	.073	-.040	-.300	-.026
CADMIUM	.053	-.000	.087	-.089	-.120	.043	-.058	.021	.239
BORON	-.007	-.121	-.102	-.071	.089	-.010	-.056	-.210	-.011
GERMANIUM	-.049	.091	-.021	.078	-.064	.001	.010	.140	-.073
PHOSPHOROUS	.055	-.181	-.053	.005	.193	.097	-.052	-.201	-.135
CHROMIUM	.108	.587	-.022	.365	-.171	.031	.031	.408	-.049
IRON	.016	.503	.016	.133	-.161	-.178	.051	.497	-.133
SODIUM	.082	-.047	.098	-.051	-.165	.047	-.067	-.020	.244
SILVER	-.137	-.187	-.025	-.180	.301	.070	-.079	-.314	.082
CALCIUM	.221	-.128	.064	-.170	-.136	-.062	-.067	-.109	.091
MERCURY	.191	.045	-.140	.138	.238	.158	-.009	-.105	-.100
ALUMINUM	.140	-.201	.150	.016	-.142	.020	-.041	-.075	.055
TIN	.044	.248	-.081	.036	-.120	.011	-.012	.195	-.006
ARSENIC	-.096	.144	-.255	-.059	.297	-.023	-.030	-.082	-.143
MOLYBDENUM	.023	.514	-.082	.271	-.167	-.170	.027	.443	-.134
COBALT	.059	-.110	-.006	-.015	-.163	.027	-.055	-.139	.234
POTASium	.137	-.194	.095	.025	-.036	.027	-.057	-.182	-.058
GOLD	.056	-.184	-.061	.004	.218	.116	-.054	-.204	-.136
ZINC	-.016	.404	.145	.264	-.156	.104	-.089	.316	.133
PALLADIUM	-.162	-.038	-.010	-.262	-.110	-.514	.001	.190	-.061
GALLIUM	.026	-.043	.016	.136	-.026	.044	-.043	-.114	.040
LEAD	.030	.224	-.080	.088	-.065	.111	-.076	.074	.175
ANTIMONY	.035	.011	.097	-.047	-.092	.087	-.055	.015	.241
MANGANESE	.146	.078	.103	-.124	-.185	-.019	-.055	.088	.111
NICKEL	.033	-.002	.103	-.050	-.088	.093	-.054	.005	.243

TABLE C-36

STATION STR36

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.234	-.148	.100	-.408	.172	-.244	-.070	-.018	-.022
COPPER	-.395	-.109	.178	-.031	.280	.137	-.099	-.089	.065
MAGNESIUM	-.146	-.173	.242	-.306	-.036	-.294	-.107	.049	.021
CADMIUM	-.403	.080	.029	.096	.321	.186	-.046	-.024	-.004
BORON	.054	-.117	.012	-.418	-.157	-.434	-.036	.117	-.041
GERMANIUM	-.407	.053	.044	.069	.329	.176	-.051	-.039	.002
PHOSPHOROUS	-.421	.035	.078	.081	.311	.178	-.073	-.033	.017
CHROMIUM	-.420	-.100	.054	-.291	.189	-.204	-.102	.042	-.011
IRON	-.425	-.091	.129	-.135	.227	-.038	-.116	-.004	.030
SODIUM	.121	-.180	.191	-.180	-.186	-.147	-.065	.006	.036
SILVER	-.404	.020	.046	.043	.344	.179	-.054	-.070	.004
CALCIUM	-.390	.078	.049	.096	.340	.197	-.038	-.035	-.020
MERCURY	-.413	.013	.054	.039	.341	.174	-.059	-.069	.009
ALUMINUM	.088	-.134	.045	-.412	-.178	-.425	-.037	.108	-.036
TIN	-.405	.070	.036	.084	.326	.184	-.049	-.030	-.001
ARSENIC	-.361	-.077	.100	-.086	.085	-.049	-.119	.038	.034
MOLYBDENUM	-.407	.071	.032	.087	.325	.182	-.049	-.029	-.004
COBALT	-.410	.024	.097	.114	.291	.200	-.080	-.041	.035
POTASIUM	.234	-.101	-.143	.007	.252	.137	.012	-.213	-.078
GOLD	-.404	.062	.038	.070	.330	.181	-.051	-.034	-.004
ZINC	-.374	-.121	.198	-.078	.189	-.013	-.120	-.036	.056
PALLADIUM	-.410	-.067	.070	-.038	.381	.167	-.066	-.138	.006
GALLIUM	.260	-.104	-.163	-.015	.149	.102	.034	-.201	-.073
LEAD	-.409	.073	.041	.089	.322	.180	-.051	-.023	-.003
ANTIMONY	-.201	.202	-.103	.221	.236	.260	.058	-.008	-.014
MANGANESE	-.385	-.134	.117	-.287	.177	-.184	-.111	.016	.010
NICKEL	-.049	-.079	.013	-.404	-.181	-.480	-.010	.170	-.002

TABLE C-37

STATION NIP37

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.033	.343	-.047	.309	.036	.213	.102	.180	-.01
COPPER	.275	.005	-.205	-.089	-.103	-.099	.173	-.029	-.049
MAGNESIUM	.085	-.263	.136	-.105	-.085	-.042	-.065	-.159	.060
CADMIUM	-.229	.005	-.098	.062	.381	.278	.025	-.196	-.031
BORON	-.309	-.082	-.039	-.102	.140	-.000	-.021	.043	-.081
GERMANIUM	-.204	.095	-.089	.148	.326	.296	.037	-.102	-.037
PHOSPHOROUS	.119	-.171	.032	-.275	-.243	-.294	-.046	.074	.02
CHROMIUM	-.155	.130	-.087	.198	.316	.332	.060	-.103	-.021
IRON	-.218	.036	-.102	.101	.370	.299	.033	-.175	-.041
SODIUM	.178	-.162	.125	-.218	-.264	-.255	-.048	.061	.027
SILVER	-.033	.293	-.077	.271	.149	.255	.096	.092	-.021
CALCIUM	.188	-.143	.143	-.149	-.288	-.251	-.038	.067	.051
MERCURY	-.088	.254	-.083	.260	.132	.260	.085	.097	-.037
ALUMINUM	-.134	.170	-.076	.228	.085	.221	.055	.090	-.06
TIN	-.274	-.007	-.079	.109	.294	.250	.009	-.101	-.05
ARSENIC	-.297	-.117	-.102	-.026	.422	.286	-.016	-.274	-.029
MOLYBDENUM	-.191	.114	-.089	.159	.318	.298	.041	-.089	-.035
COBALT	-.232	-.153	-.068	.032	.384	.336	-.014	-.327	-.001
POTASIUM	.030	.329	-.042	.298	.043	.211	.101	.172	-.016
GOLD	-.072	-.132	-.074	-.489	-.107	-.508	-.020	.134	-.058
ZINC	-.150	-.149	-.096	-.046	.413	.259	.036	-.335	-.031
PALLADIUM	.022	.336	-.046	.303	.063	.227	.102	.162	-.01
GALLIUM	.043	.350	-.043	.315	.021	.212	.103	.191	-.013
LEAD	-.207	.020	-.100	.079	.369	.285	.036	-.179	-.047
ANTIMONY	-.123	.124	-.123	.113	.282	.208	.056	-.084	-.001
MANGANESE	-.250	-.066	-.100	.012	.406	.267	.006	-.260	-.038
NICKEL	.012	-.022	-.057	-.375	-.025	-.401	.006	.099	-.029

TABLE C-38

STATION CLE38

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.333	.031	.178	-.039	.085	-.094	-.147	.134	.006
COPPER	-.123	.672	-.071	.479	-.002	.084	-.044	.487	-.116
MAGNESIUM	-.348	.020	.170	-.048	.108	-.084	-.147	.118	-.002
CADMIUM	-.320	.006	.179	-.077	.072	-.126	-.147	.130	.003
BORON	-.373	-.089	.223	-.157	.246	-.027	-.130	.002	.024
GERMANIUM	-.327	-.135	.008	-.043	.147	-.029	-.114	-.092	-.016
PHOSPHOROUS	-.051	-.010	.230	-.063	-.128	-.296	-.079	.177	-.025
CHROMIUM	-.297	-.044	.170	-.057	.027	-.114	-.143	.082	.025
IRON	-.345	-.062	.156	-.097	.145	-.075	-.144	.022	.017
SODIUM	-.336	-.009	.263	-.042	.246	.046	-.126	.037	.017
SILVER	-.358	.016	.214	-.059	.104	-.077	-.145	.130	.025
CALCIUM	-.290	-.057	.170	-.106	.102	-.087	-.141	.034	.008
MERCURY	-.296	-.048	.127	-.106	.042	-.142	-.142	.106	-.021
ALUMINUM	-.354	-.083	.180	-.137	.249	-.023	-.132	-.015	.007
TIN	-.330	.028	.175	-.043	.079	-.096	-.147	.132	.006
ARSENIC	-.330	.004	.163	-.074	.087	-.113	-.147	.134	-.002
MOLYBDENUM	-.334	.006	.175	-.059	.100	-.095	-.147	.116	.003
COBALT	-.327	.020	.171	-.039	.074	-.091	-.147	.121	.010
POTASIUM	-.392	-.238	.003	-.524	-.045	-.629	-.063	.169	-.035
GOLD	-.339	.015	.124	-.124	.015	-.208	-.143	.181	-.010
ZINC	-.188	.533	-.059	.426	-.015	.037	-.077	.405	.088
PALLADIUM	-.294	-.000	.184	-.049	.045	-.107	-.146	.119	.013
GALLIUM	-.274	.009	.083	.020	-.000	-.094	-.130	.092	.007
LEAD	-.279	.048	.198	-.013	.054	-.096	-.146	.142	.009
ANTIMONY	-.226	-.203	.100	-.277	.127	-.176	-.115	-.024	-.034
MANGANESE	-.338	.016	.179	-.057	.086	-.106	-.147	.129	.007
NICKEL	-.252	.143	.049	.175	.030	.020	-.086	.177	-.004

TABLE C-39

STATION RIN39

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.141	-.148	-.201	.049	-.108	.108	.051	-.193	.01
COPPER	-.102	.075	-.057	.223	-.107	-.006	-.051	.045	.010
MAGNESIUM	-.256	-.099	.368	-.172	.139	.059	-.037	.050	.118
CADMIUM	.309	-.027	-.134	.032	-.072	.107	.157	-.124	.01
BORON	-.165	-.098	-.039	.137	.108	.090	-.087	-.171	-.00
GERMANIUM	.325	-.044	-.156	.077	-.108	.101	.112	-.152	.026
PHOSPHOROUS	-.182	.541	.111	.375	.063	.151	-.029	.427	-.01
CHROMIUM	.313	-.054	-.141	.031	-.077	.125	.090	-.129	.05
IRON	.329	-.036	-.145	.041	-.075	.117	.094	-.149	.053
SODIUM	.089	.204	-.110	.041	-.129	.002	.037	.136	-.034
SILVER	.210	-.010	-.047	.032	.032	.174	.080	-.113	.07
CALCIUM	.272	-.016	-.116	-.015	-.053	.131	.076	-.116	.06
MERCURY	.338	.016	-.178	.069	-.080	.125	.096	-.115	.029
ALUMINUM	.027	-.224	.023	-.234	-.247	-.254	-.060	.063	-.03
TIN	.342	-.008	-.185	.050	-.061	.107	.136	-.144	.00
ARSENIC	.350	.016	-.162	.060	-.114	.079	.173	-.099	.018
MOLYBDENUM	.299	-.031	-.119	.022	-.059	.116	.099	-.134	.06
COBALT	.288	-.020	-.161	.057	-.138	.049	.152	-.140	.02
POTASIUM	.265	-.121	-.181	.085	-.136	.097	.064	-.192	.056
GOLD	.332	-.074	-.146	.030	-.092	.130	.095	-.139	.055
ZINC	-.081	.679	-.075	.510	-.026	.106	-.021	.479	-.11
PALLADIUM	.382	-.082	-.158	.031	-.158	.089	.036	-.165	.08
GALLIUM	.341	.064	-.211	.141	-.118	.135	.083	-.064	.026
LEAD	.318	-.037	-.142	.011	-.084	.075	.143	-.130	.03
ANTIMONY	.295	.009	-.157	.052	-.123	.029	.252	-.064	-.05
MANGANESE	-.161	-.133	.329	-.158	.133	.093	-.005	-.012	.137
NICKEL	.282	.015	-.151	.052	-.130	.015	.262	-.047	-.066

TABLE C-40

STATION AUP40

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.167	-.173	.121	-.212	-.272	-.281	-.049	.048	.039
COPPER	-.151	-.307	.034	-.515	-.186	-.625	-.035	.126	-.010
MAGNESIUM	.193	-.160	.127	-.157	-.270	-.224	-.049	.035	.047
CADMIUM	.190	-.182	.157	-.171	-.269	-.247	-.049	.027	.049
BORON	.215	-.167	.147	-.090	-.259	-.168	-.047	.010	.062
GERMANIUM	.167	-.173	.123	-.214	-.272	-.283	-.049	.051	.037
PHOSPHOROUS	.167	-.173	.123	-.214	-.272	-.283	-.049	.051	.037
CHROMIUM	.206	-.141	.124	-.102	-.264	-.165	-.048	.035	.051
IRON	.217	-.177	.158	-.071	-.256	-.150	-.047	-.010	.067
SODIUM	.211	-.116	.180	-.058	-.225	-.067	-.041	.068	.016
SILVER	.169	-.168	.118	-.215	-.272	-.279	-.049	.056	.034
CALCIUM	.200	-.161	.129	-.138	-.268	-.211	-.049	.019	.054
MERCURY	.199	-.117	.124	-.080	-.256	-.128	-.047	.060	.041
ALUMINUM	.217	-.171	.170	-.098	-.259	-.156	-.047	.019	.049
TIN	.171	-.178	.136	-.209	-.271	-.280	-.049	.054	.038
ARSENIC	.193	-.134	.071	-.151	-.263	-.203	-.048	.029	.047
MOLYBDENUM	.167	-.173	.123	-.214	-.272	-.283	-.049	.051	.037
COBALT	.171	-.174	.133	-.196	-.270	-.272	-.049	.050	.043
POTASIUM	.167	-.173	.123	-.214	-.272	-.282	-.049	.051	.037
GOLD	.135	-.160	.068	-.238	-.267	-.299	-.049	.069	.030
ZINC	.188	-.217	.178	-.059	-.240	-.159	-.044	-.036	.080
PALLADIUM	.166	-.170	.120	-.209	-.272	-.277	-.049	.053	.037
GALLIUM	.161	-.174	.119	-.224	-.272	-.292	-.049	.056	.035
LEAD	.117	-.244	.136	-.220	-.261	-.328	-.048	.017	.057
ANTIMONY	.221	-.161	.170	-.119	-.265	-.186	-.048	.023	.055
MANGANESE	.177	-.173	.131	-.199	-.272	-.269	-.049	.044	.041
NICKEL	.236	-.194	.264	-.113	-.244	-.170	-.044	-.026	.066

TABLE C-41

STATION RIN41

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.021	-.173	.020	.026	.100	.030	.010	-.157	.01
COPPER	.009	.106	-.084	.253	-.051	.025	.029	.082	-.024
MAGNESIUM	-.052	-.177	.031	-.001	.172	.049	.002	-.197	.028
CADMIUM	-.016	-.178	.030	.028	.060	.020	.011	-.128	.01
BORON	-.320	-.390	.347	-.308	.177	-.090	-.064	-.134	.01
GERMANIUM	-.051	-.136	-.008	-.060	-.029	-.011	-.003	-.035	-.034
PHOSPHOROUS	-.111	-.088	-.015	-.103	-.052	-.012	-.032	.021	-.079
CHROMIUM	-.028	-.190	.036	.008	.061	.021	.011	.126	.01
IRON	-.081	-.214	.028	-.042	.041	.000	.006	-.109	-.008
SODIUM	-.158	-.142	-.095	-.146	.359	.084	-.037	-.302	-.029
SILVER	-.036	-.196	.020	-.010	.073	.020	.004	-.142	.01
CALCIUM	-.095	-.211	-.035	-.069	.191	.047	-.012	-.231	-.01
MERCURY	-.047	-.147	-.002	-.053	-.013	-.006	.001	-.051	-.027
ALUMINUM	.009	-.208	.060	-.059	-.033	-.012	-.003	-.068	-.073
TIN	-.047	-.123	-.006	-.069	-.039	-.015	-.008	-.019	-.01
ARSENIC	-.048	-.166	.003	-.053	-.016	-.017	-.001	-.056	-.025
MOLYBDENUM	-.025	-.186	.019	-.009	.026	.007	.008	-.105	-.003
COBALT	.008	-.187	.007	-.017	.002	.020	-.007	-.007	-.01
POTASIUM	-.120	-.127	-.087	-.180	.014	-.046	-.037	-.032	-.01
GOLD	-.322	-.275	-.049	-.419	-.071	-.447	-.029	.088	-.077
ZINC	-.159	-.141	.219	-.030	.045	.044	-.014	.023	.01
PALLADIUM	-.098	-.167	-.057	-.121	.134	.020	-.012	-.165	-.01
GALLIUM	-.063	-.157	-.029	-.066	.023	.002	.001	-.088	-.033
LEAD	-.091	-.183	.080	-.090	.007	.000	-.008	-.043	.001
ANTIMONY	-.059	-.137	-.002	-.068	-.016	-.007	-.002	-.040	-.01
MANGANESE	-.002	-.158	.034	.042	.073	.022	.013	-.132	.023
NICKEL	-.165	-.202	.182	-.123	.049	.023	-.023	-.031	.035

TABLE C-42

STATION CLE42

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.133	-.053	-.016	-.086	.275	-.013	.105	-.105	-.207
COPPER	-.194	-.088	.038	-.137	.169	-.121	.017	-.004	-.184
MAGNESIUM	.040	-.135	.305	-.087	.052	-.043	-.002	-.036	-.102
CADMIUM	.119	-.136	.326	-.069	-.025	-.041	-.008	-.024	-.063
BORON	-.040	-.045	.119	.064	-.076	-.051	-.011	-.019	-.059
GERMANIUM	-.167	.054	-.062	.068	-.081	-.048	-.046	.157	-.090
PHOSPHOROUS	-.032	-.073	.199	-.048	.063	-.069	.018	.017	-.170
CHROMIUM	.106	-.123	.304	-.059	-.022	-.054	.000	-.010	-.091
IRON	.052	-.109	.278	-.059	.014	-.062	.008	.001	-.125
SODIUM	-.293	-.224	.043	-.328	.199	-.218	-.022	-.059	-.092
SILVER	-.191	-.030	.089	-.051	.174	-.064	.035	.032	-.204
CALCIUM	.123	-.135	.335	-.068	-.036	-.041	-.008	-.017	-.057
MERCURY	-.142	-.162	-.004	-.202	-.020	-.251	.000	.058	-.115
ALUMINUM	.291	-.154	.223	-.044	-.054	.004	.059	-.096	-.092
TIN	.185	.029	-.087	.027	-.051	-.020	.277	.005	-.151
ARSENIC	-.186	-.026	.095	-.046	.159	-.068	.037	.046	-.204
MOLYBDENUM	.087	-.120	.298	-.060	-.008	-.057	.003	-.006	-.103
COBALT	-.149	-.052	.133	-.055	.132	-.072	.032	.038	-.202
POTASIUM	.128	-.060	.034	.006	-.008	-.044	-.015	-.065	.144
GOLD	-.199	.252	-.128	.199	-.090	-.094	-.054	.297	-.142
ZINC	.020	-.129	.284	-.086	.070	-.046	.002	-.036	-.119
PALLADIUM	-.194	.154	.003	.125	-.014	-.106	-.039	.226	-.131
GALLIUM	-.236	-.004	.109	-.035	.149	-.077	.010	.082	-.182
LEAD	.009	-.213	-.004	-.243	-.203	-.326	-.018	.038	-.041
ANTIMONY	-.084	-.151	-.028	-.245	-.025	-.281	.034	.079	-.153
MANGANESE	.033	-.127	.270	-.082	.067	-.047	.002	-.043	-.121
NICKEL	.093	-.144	.332	-.082	.007	-.038	-.008	-.035	-.069

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HARRIS CORP SYOSSET NY PRD ELECTRONICS DIV

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MM&T PROGRAM TO ESTABLISH PRODUCTION TECHNIQUES FOR THE AUTOMAT--ET

MAR 81 J D BASILE, R W SPACIE, G P ALLENDORF

DAAB07-77-C-0561

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TABLE C-43

STATION CLE43

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.115	-.015	.044	.016	-.075	-.027	-.013	-.019	-.041
COPPER	.215	-.028	-.135	.052	-.120	.118	-.056	-.122	.161
MAGNESIUM	-.057	.544	-.065	.416	-.086	.017	.139	.419	-.126
CADMIUM	.027	-.276	.236	-.294	-.138	-.264	-.028	.137	-.007
BORON	-.193	.028	-.136	-.013	.355	.109	-.019	-.222	-.031
GERMANIUM	-.057	-.200	-.192	-.064	.229	.182	-.078	-.304	-.013
PHOSPHOROUS	-.163	-.098	.342	-.137	.085	.066	.058	.030	.119
CHROMIUM	-.304	.302	.152	.247	.058	.071	-.075	.303	.001
IRON	-.240	-.156	-.120	-.139	.342	.092	-.043	-.264	-.051
SODIUM	-.099	.249	-.082	.202	-.054	-.103	.125	.203	-.110
SILVER	-.223	-.040	.114	.045	.017	-.003	-.060	.040	.051
CALCIUM	-.046	.474	-.075	.358	-.115	-.039	.152	.396	-.121
MERCURY	-.369	.206	.144	.166	.126	.071	-.088	.220	.004
ALUMINUM	-.009	.129	.109	.108	-.088	-.053	.061	.155	-.065
TIN	.050	-.159	-.139	.014	-.045	.140	-.065	-.159	.001
ARSENIC	.032	-.176	-.173	.008	.018	.150	-.061	-.196	-.006
MOLYBDENUM	.033	-.213	-.095	-.043	-.069	.094	-.069	-.124	-.004
COBALT	.102	-.035	.031	.016	-.075	-.012	-.019	-.030	-.051
POTASIUM	-.078	.288	.110	.241	-.063	.016	.110	.266	-.061
GOLD	.118	-.034	.022	.012	-.083	-.005	-.023	-.034	-.058
ZINC	-.088	.435	-.039	.381	-.080	.118	-.093	.303	.081
PALLADIUM	-.114	.276	.139	.223	-.050	.012	.103	.274	-.051
GALLIUM	-.127	.318	.030	.279	-.049	.016	.109	.280	-.056
LEAD	.011	-.270	-.034	-.143	-.175	-.084	-.070	-.001	-.022
ANTIMONY	.012	-.158	-.103	.012	-.055	.138	-.063	-.098	-.011
MANGANESE	-.361	.134	.220	.080	.078	.000	-.074	.241	.041
NICKEL	-.044	.477	-.049	.373	-.083	.020	.165	.368	-.114

TABLE C-44

STATION CLE44

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.177	.040	-.014	.086	.019	.028	.029	-.106	.044
COPPER	-.293	-.269	-.068	-.564	-.079	-.656	-.013	.139	-.043
MAGNESIUM	-.044	-.014	-.048	-.107	.117	-.071	-.016	-.098	.017
CADMIUM	.345	.041	-.138	.080	-.057	.084	.125	-.114	-.002
BORON	.365	-.023	-.154	.067	-.100	.087	.137	-.147	.023
GERMANIUM	.374	.071	-.187	.144	-.124	.094	.156	-.086	-.008
PHOSPHOROUS	-.111	-.267	-.119	-.505	-.109	-.579	.048	.064	-.033
CHROMIUM	.351	.018	-.134	.063	-.067	.063	.121	-.123	-.011
IRON	.362	-.021	-.142	.032	-.100	.032	.125	-.130	-.015
SODIUM	-.083	-.219	.350	-.164	.051	-.043	-.048	-.087	.188
SILVER	.338	.023	-.118	.072	-.042	.079	.102	-.130	-.023
CALCIUM	.341	-.064	-.154	-.013	-.067	.017	.095	-.216	-.041
MERCURY	.379	-.011	-.148	.066	-.097	.087	.132	-.142	-.022
ALUMINUM	.370	-.048	-.150	.062	-.127	.056	.107	-.153	-.007
TIN	.359	.006	-.175	.061	-.093	.092	.158	-.123	-.001
ARSENIC	.359	.006	-.175	.061	-.093	.091	.159	-.123	-.003
MOLYBDENUM	.371	.013	-.165	.069	-.097	.089	.156	-.123	-.004
COBALT	.379	-.012	-.171	.069	-.095	.100	.123	-.132	.002
POTASIUM	-.138	-.232	-.092	-.400	-.128	-.597	-.008	.066	-.036
GOLD	-.318	-.170	-.085	-.477	-.089	-.647	-.029	.207	-.058
ZINC	-.276	-.272	-.079	-.558	-.082	-.651	-.006	.127	-.039
PALLADIUM	.291	.014	-.098	.140	-.016	.057	.032	-.168	-.040
GALLIUM	.364	-.014	-.108	.078	-.096	.066	.094	-.139	-.037
LEAD	.292	-.070	-.181	-.081	-.115	-.076	.140	-.097	-.024
ANTIMONY	.375	-.006	-.160	.060	-.097	.090	.147	-.134	-.008
MANGANESE	.142	.098	-.036	.072	.023	.029	.044	-.029	.022
NICKEL	-.322	-.124	.291	-.320	.024	-.188	-.047	.137	.062

TABLE C-45

STATION COT45

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.164	.121	-.057	.060	-.170	-.063	.295	.097	-.05
COPPER	.088	.074	-.034	.016	-.196	-.084	.250	.117	-.05a
MAGNESIUM	.103	.077	-.050	-.007	-.190	-.134	.284	.120	-.066
CADMIUM	.096	.076	-.055	-.026	-.189	-.163	.288	.127	-.06
BORON	.126	.126	.005	.073	-.166	-.050	.280	.124	-.06
GERMANIUM	.106	.084	-.021	.055	-.120	-.033	.268	.095	-.092
PHOSPHOROUS	-.151	.123	.102	.010	-.506	-.133	.036	.213	.11
CHROMIUM	.080	.060	-.055	-.048	-.196	-.185	.283	.132	-.06
IRON	.096	.073	-.052	-.020	-.192	-.152	.285	.125	-.066
SODIUM	.138	.111	-.050	.043	-.181	-.074	.289	.111	-.064
SILVER	.129	.096	-.045	.040	-.181	-.076	.284	.106	-.06
CALCIUM	.004	-.000	-.058	-.156	-.211	-.302	.259	.157	-.06
MERCURY	.133	.120	-.048	.041	-.190	-.078	.286	.121	-.065
ALUMINUM	.115	.005	-.124	-.144	-.262	-.260	.191	.102	.07
TIN	.240	.097	-.105	.063	-.235	-.022	.246	.054	.03
ARSENIC	-.148	.126	.103	.015	-.505	-.128	.036	.212	.113
MOLYBDENUM	.085	.062	-.056	-.045	-.192	-.181	.285	.129	-.06a
COBALT	.084	.042	-.037	.006	-.173	-.077	.235	.095	-.06
POTASIUM	-.223	-.262	-.064	-.078	-.140	-.203	-.036	-.086	-.01
GOLD	-.313	.279	.176	.163	.155	.074	-.073	.214	.061
ZINC	.135	.108	-.045	.047	-.180	-.075	.289	.109	-.06
PALLADIUM	.145	-.104	.102	-.009	-.175	-.007	-.047	-.036	.07
GALLIUM	-.012	.027	.153	.009	-.298	-.070	-.015	.132	.110
LEAD	.061	.166	-.068	-.052	-.148	-.075	.101	.152	-.03
ANTIMONY	.137	.117	-.054	.037	-.186	-.075	.285	.118	-.07
MANGANESE	.104	.081	-.051	-.007	-.190	-.138	.286	.122	-.06b
NICKEL	.093	.069	-.054	-.029	-.192	-.162	.285	.126	-.068

TABLE C-46

STATION WSH47

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	-.072	-.226	-.136	-.060	.000	.037	.016	-.180	-.060
COPPER	-.097	-.224	-.120	-.069	-.030	.020	-.005	-.150	-.064
MAGNESIUM	-.092	-.276	-.145	-.178	-.135	-.118	-.022	-.101	-.054
CADMIUM	-.068	-.272	-.147	-.224	-.173	-.189	-.027	-.054	-.043
BORON	.202	-.147	.285	-.044	-.112	-.020	-.011	-.043	-.012
GERMANIUM	.344	-.016	-.188	.049	-.097	.099	.131	-.140	.028
PHOSPHOROUS	-.107	-.224	-.122	-.098	-.110	-.036	-.015	-.099	-.059
CHROMIUM	-.077	-.268	-.145	-.197	-.162	-.149	-.022	-.072	-.051
IRON	-.091	-.260	-.139	-.160	-.143	-.102	-.017	-.090	-.057
SODIUM	-.126	-.227	-.121	-.071	.014	.024	-.016	-.166	-.061
SILVER	-.114	-.198	-.104	-.046	-.043	.028	-.006	-.116	-.066
CALCIUM	-.078	-.266	-.143	-.218	-.172	-.184	-.028	-.048	-.044
MERCURY	-.113	-.177	-.108	-.051	-.059	.025	-.007	-.097	-.069
ALUMINUM	.140	-.221	-.187	-.270	-.203	-.260	.018	-.031	-.002
TIN	.213	-.124	-.181	.008	-.060	.131	-.039	-.203	.080
ARSENIC	-.064	-.247	-.132	-.078	-.064	.009	.003	-.165	-.062
MOLYBDENUM	-.080	-.269	-.145	-.187	-.156	-.135	-.020	-.082	-.053
COBALT	-.056	-.219	-.140	-.059	-.074	.034	-.018	-.146	-.041
POTASIUM	-.056	-.311	-.134	-.126	.067	.002	-.012	-.288	-.038
GOLD	.182	-.297	-.228	-.181	-.098	-.043	.042	-.277	-.061
ZINC	-.100	-.265	-.139	-.156	-.123	-.092	-.020	-.105	-.057
PALLADIUM	.269	-.403	-.215	-.267	-.143	-.147	.042	-.350	-.006
GALLIUM	.224	-.427	-.218	-.235	-.109	-.110	.039	-.383	-.012
LEAD	.213	-.073	.182	-.114	-.186	-.076	-.020	.030	-.008
ANTIMONY	-.040	-.181	-.144	-.057	-.117	.027	.006	-.122	-.038
MANGANESE	-.091	-.274	-.144	-.172	-.124	-.105	-.020	-.110	-.055
NICKEL	-.065	-.277	-.150	-.217	-.171	-.174	-.024	-.068	-.046

TABLE C-47

STATION CLE48

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.067	-.116	.100	.022	-.118	-.073	-.022	-.042	.061
COPPER	.047	.019	.051	-.018	-.141	-.073	-.026	.062	.026
MAGNESIUM	.020	-.118	-.098	-.224	-.196	-.278	-.018	.109	.007
CADMIUM	.014	-.098	-.101	-.217	-.183	-.264	-.014	.118	.002
BORON	.222	-.103	.308	-.022	-.102	-.006	-.011	-.020	-.002
GERMANIUM	-.176	.161	-.031	.058	.399	.286	-.012	-.105	-.009
PHOSPHOROUS	.016	.252	.008	.205	.008	.184	.074	.179	.006
CHROMIUM	.020	-.113	-.100	-.233	-.181	-.272	-.017	.103	.002
IRON	.021	-.045	-.094	-.170	-.174	-.218	.008	.149	-.004
SODIUM	.011	-.081	.026	.001	-.161	-.094	-.043	-.009	.043
SILVER	-.042	.258	.106	.197	.062	.198	.083	.193	.007
CALCIUM	.012	-.093	-.098	-.213	-.182	-.258	-.013	.123	.004
MERCURY	-.050	.231	.015	-.001	-.060	.007	-.016	.207	-.016
ALUMINUM	.019	-.162	-.097	-.265	-.180	-.296	-.032	.062	.006
TIN	-.029	.123	.099	.112	.082	.213	.020	.082	.052
ARSENIC	-.380	-.311	-.054	-.757	-.052	-.943	-.013	.284	-.025
MOLYBDENUM	.018	-.098	-.095	-.223	-.175	-.257	-.014	.117	.003
COBALT	.095	.270	-.087	.173	-.097	.072	.129	.232	-.032
POTASIUM	-.119	.120	.249	.070	.105	.159	.062	.142	.049
GOLD	-.182	.010	-.109	-.111	.385	.150	-.028	-.219	-.030
ZINC	.022	-.077	-.094	-.193	-.193	-.253	-.005	.139	.004
PALLADIUM	-.192	-.130	.025	-.252	.369	.051	-.053	-.239	.007
GALLIUM	.023	.003	-.141	.101	.247	.156	-.014	-.252	-.090
LEAD	.187	-.028	.222	-.095	-.162	-.073	-.025	.070	-.015
ANTIMONY	.002	.278	.051	.101	-.008	.153	.048	.206	.012
MANGANESE	.027	-.108	-.092	-.219	-.194	-.272	-.014	.114	.006
NICKEL	.017	-.109	-.103	-.226	-.183	-.270	-.015	.111	.001

TABLE C-48

STATION CLE49

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.255	.070	-.315	.154	-.183	-.087	.023	-.042	-.092
COPPER	.255	.115	-.351	.151	-.179	-.080	.026	-.019	-.111
MAGNESIUM	.155	-.032	-.282	-.096	-.242	-.263	.004	.072	-.060
CADMIUM	.119	-.031	-.248	-.123	-.226	-.262	.004	.099	-.051
BORON	.240	-.084	.274	-.002	-.113	-.009	-.007	-.016	-.014
GERMANIUM	.133	.257	-.354	.208	.157	.167	.059	-.082	-.112
PHOSPHOROUS	.207	.340	-.304	.315	-.121	.104	.097	.160	-.120
CHROMIUM	.127	-.046	-.251	-.134	-.222	-.267	-.001	.078	-.051
IRON	.180	.050	-.323	-.028	-.233	-.217	.019	.100	-.082
SODIUM	.160	.049	-.282	.109	-.192	-.098	-.004	-.024	-.071
SILVER	.257	.172	-.392	.212	-.163	-.027	.050	.002	-.127
CALCIUM	.122	-.029	-.250	-.121	-.226	-.258	.005	.099	-.050
MERCURY	.238	.216	-.368	.169	-.174	-.053	.034	.053	-.127
ALUMINUM	.038	-.155	-.124	-.254	-.187	-.299	-.028	.057	-.004
TIN	.216	.297	-.351	.320	-.131	.097	.068	.098	-.124
ARSENIC	.255	.120	-.378	.160	-.156	-.068	.033	-.030	-.122
MOLYBDENUM	.154	-.009	-.285	-.092	-.231	-.246	.008	.085	-.062
COBALT	.263	.250	-.405	.244	-.179	-.027	.038	.080	-.130
POTASIUM	.192	.339	-.252	.337	-.078	.167	.087	.135	-.082
GOLD	.042	.116	-.323	.031	.222	.077	.032	-.175	-.110
ZINC	.183	.030	-.319	-.033	-.246	-.228	.019	.090	-.079
PALLADIUM	-.054	.026	-.259	.095	.029	.059	.003	-.055	-.131
GALLIUM	.241	.108	-.372	.155	-.129	-.057	.028	-.053	-.120
LEAD	.225	-.057	.224	-.079	-.171	-.079	-.024	.045	-.019
ANTIMONY	.250	.251	-.376	.262	-.141	.070	.025	.045	-.106
MANGANESE	.167	-.013	-.293	-.080	-.239	-.252	.009	.074	-.067
NICKEL	.125	-.042	-.259	-.120	-.228	-.262	-.001	.082	-.052

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STATION CLE50

ELECTRICAL MEASUREMENTS

CONTAMINANTS	T501	T502	T503	T504	T505	T506	T507	T508	YIELD
LITHIUM	.085	.365	-.042	.273	-.003	.213	.086	.218	-.041
COPPER	.071	.408	-.068	.322	-.048	.220	.048	.249	-.016
MAGNESIUM	-.093	-.152	-.069	-.020	-.081	-.101	-.038	-.066	.019
CADMIUM	-.034	-.015	-.078	.000	-.115	-.077	-.002	.005	.036
BORON	.172	-.043	.456	-.045	-.002	.096	-.009	.014	.038
GERMANIUM	.169	.131	.086	.130	.197	.227	.033	-.110	-.043
PHOSPHOROUS	-.071	-.133	-.056	.028	-.061	-.047	-.035	-.087	.021
CHROMIUM	.104	.342	.028	.244	.031	.234	.083	.193	-.028
IRON	.107	.366	.043	.262	.034	.240	.075	.211	-.023
SODIUM	-.237	-.202	-.221	-.190	.112	-.190	-.043	-.124	.015
SILVER	.084	.362	-.028	.265	.001	.215	.088	.219	-.039
CALCIUM	-.000	.229	-.087	.243	-.070	.125	.054	.160	-.020
MERCURY	.085	.345	.012	.230	.082	.253	.081	.167	-.034
ALUMINUM	.063	.364	-.042	.256	-.020	.191	.086	.235	-.040
TIN	.091	.352	-.066	.226	-.033	.165	.089	.242	-.052
ARSENIC	.148	.353	-.013	.269	.012	.234	.090	.183	-.054
MOLYBDENUM	.108	.364	-.066	.272	-.012	.212	.090	.208	-.048
COBALT	.083	.350	-.013	.246	.006	.216	.083	.213	-.035
POTASIUM	-.037	.025	-.085	.159	-.064	.048	.004	.004	.002
GOLD	.045	-.175	.132	-.145	.229	.043	-.042	-.263	.018
ZINC	.088	.418	-.060	.302	-.031	.218	.052	.253	-.026
PALLADIUM	.110	.350	-.012	.297	-.053	.201	.090	.229	-.043
GALLIUM	.072	.357	-.045	.295	.142	.298	.084	.105	-.039
LEAD	.091	.352	-.034	.252	-.019	.209	.084	.223	-.036
ANTIMONY	.090	.354	-.025	.251	.009	.219	.086	.208	-.039
MANGANESE	.076	.351	-.011	.246	.004	.211	.085	.218	-.034
NICKEL	-.066	-.147	-.054	.018	-.053	-.052	-.039	-.103	.031

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